

Circumstellar Mass Loss

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Branch

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Laboratory

Outline:

- A. A Brief Review of Past Approaches to the Mass Loss Problem
- B. The Infrared Spatial Interferometer (ISI) and the perspective from 11 μm
- C. New insights from imaging interferometry at 1.65-3.1 μm with the Keck Telescope

The Team:

Science:

W.C. Danchi (PI)

J. McMahon (to start Ph.D. in fall)

J. Shapiro (in between)

C.H. Townes (PI)

J. Weiner (Ph.D. student)

Engineering/Software:

J. Abele (contract ME)

R. Anderson (contract software)

P. Barale (LBNL)

W. Fitelson

D. Hale

J. Hudson

Collaborators:

E. Lipman (NIH)

B. Lopez (OCA, France)

J. Monnier (CfA, also on Aperture Masking)

P.G. Tuthill (Sydney University, also on Aperture Masking)

Examples of Stars Studied So Far with Stellar Interferometry

Type of Object	Wavelength, Instrument
1. <i>Late Stars</i> <ul style="list-style-type: none">• Supergiants• Oxygen-rich Mira Variables• Carbon Stars• Semi-Regular, Irregular Variables	11 μm, ISI 2 μm, Keck Aperture Masking 2 μm, PTI 11 μm, ISI
2. <i>Wolf-Rayet Stars</i> (High mass evolved stars, dusty WC 9)	2 μm, Keck Aperture Masking
3. <i>Herbig Ae/Be Stars</i> (Medium-to-high mass young stellar objects, with disks)	2 μm, Keck Aperture Masking 11 μm, ISI 2 μm, IOTA
4. <i>Be Stars</i> – Emission line stars (γ Cas, η Tau, φ Per, β CMi, 48 Per, ζ Tau, ψ Per)	Optical , Mark III, GI2T
5. <i>T Tauri Stars, YSO's</i> (FU Ori)	2 μm, PTI

Fringe visibility:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

I = Intensities of the fringe pattern

Complex fringe visibility:

$$V(\mathbf{b}) = \frac{1}{4\pi} \int A_n(\mathbf{s}) B(\mathbf{s}) e^{-2\pi i \mathbf{b} \cdot \mathbf{s}} d\Omega$$

$A_n(\mathbf{s})$ = normalized antenna pattern

$B(\mathbf{s})$ = radio brightness distribution

For a small field of view on the sky a two-dimensional Fourier transform gives:

$$\frac{A_n(x, y) B(x, y)}{\sqrt{1 - x^2 - y^2}} =$$

$$\int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} V(u, v) e^{2\pi i (u x + v y)} du dv$$

DUST FORMATION PROCESS

180

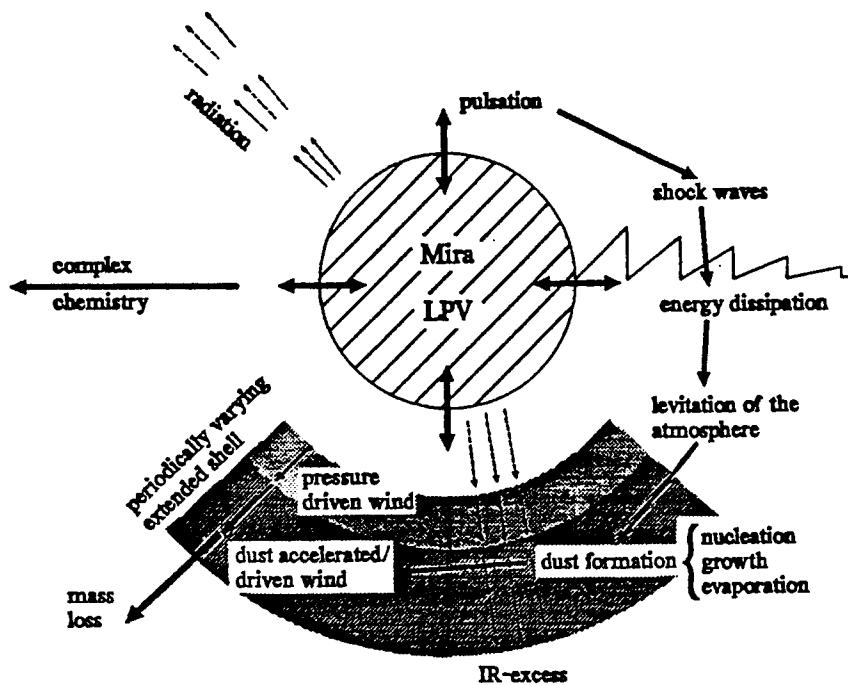


Fig. 1: Scenario of a pulsating variable showing the global shell structure and depicting essential physical "ingredients".

BASIC IDEA:

- 1) SHOCK WAVES LEVITATE ATMOSPHERE
- 2) DENSITY HIGH FAR ENOUGH FROM PHOTOSPHERE
TO NUCLEATE DUST
- 3) RADIATION PRESSURE ON DUST CAUSES IT
TO ACCELERATE
- 4) GAS ACCELERATED BY COLLISIONS WITH
DUST.

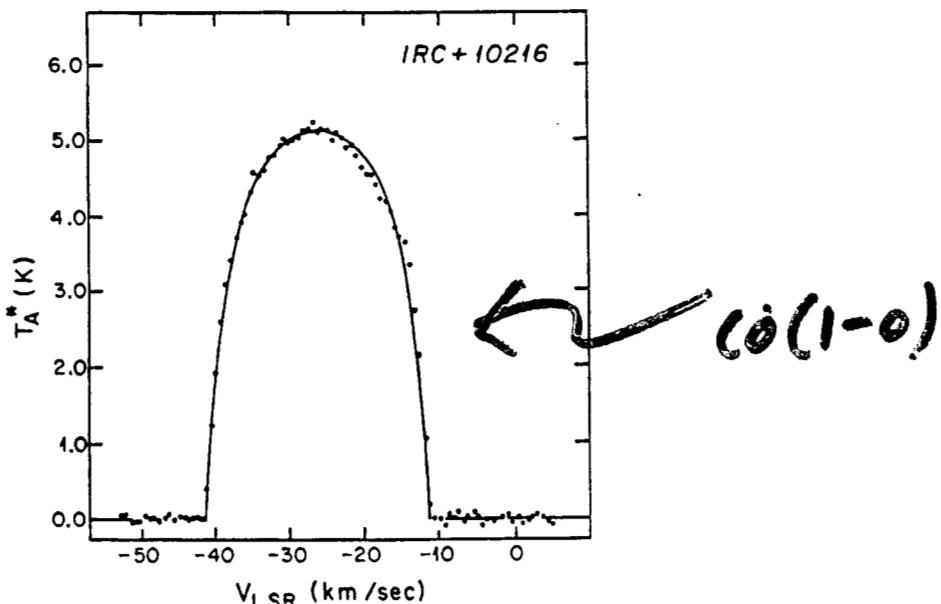
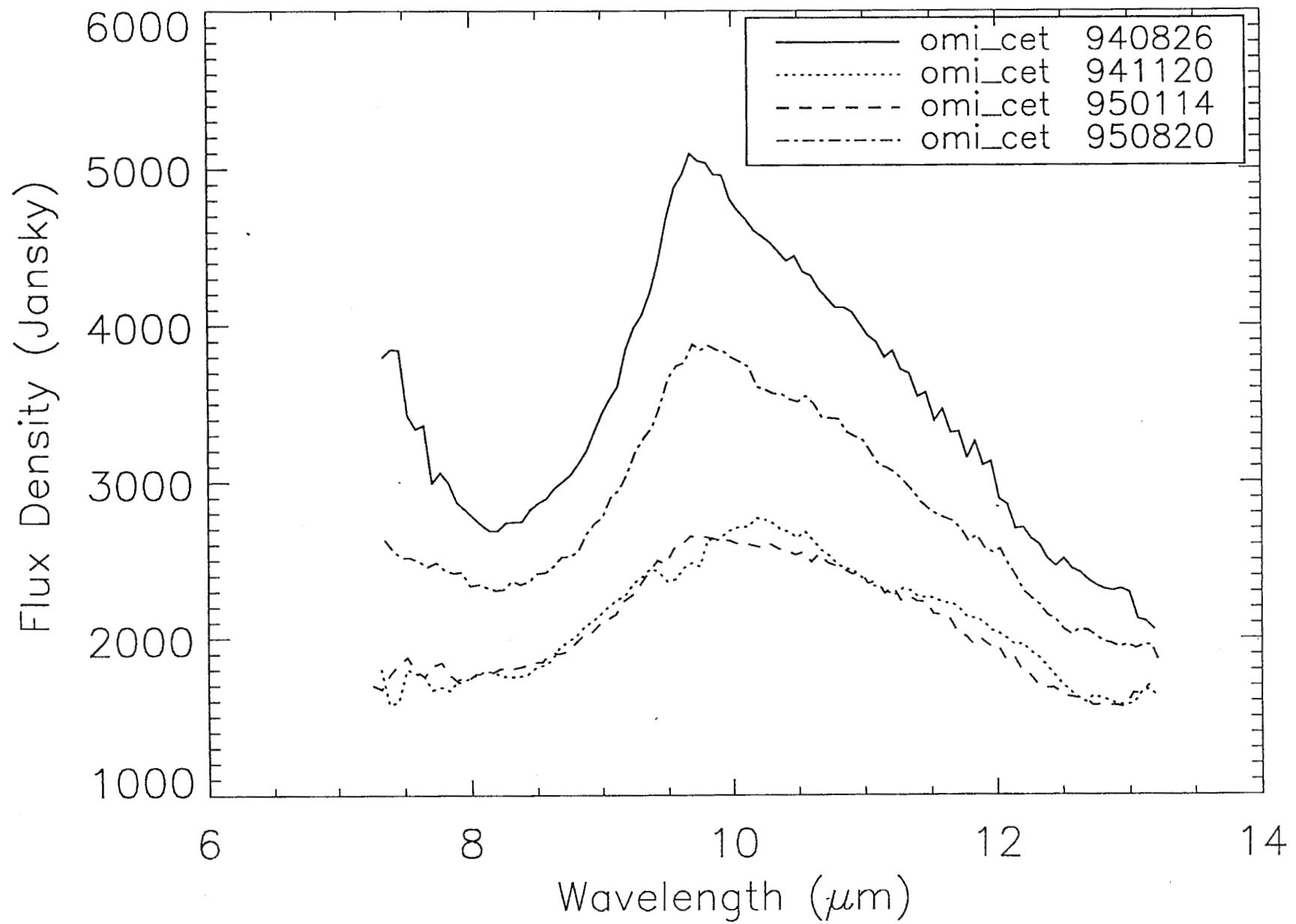


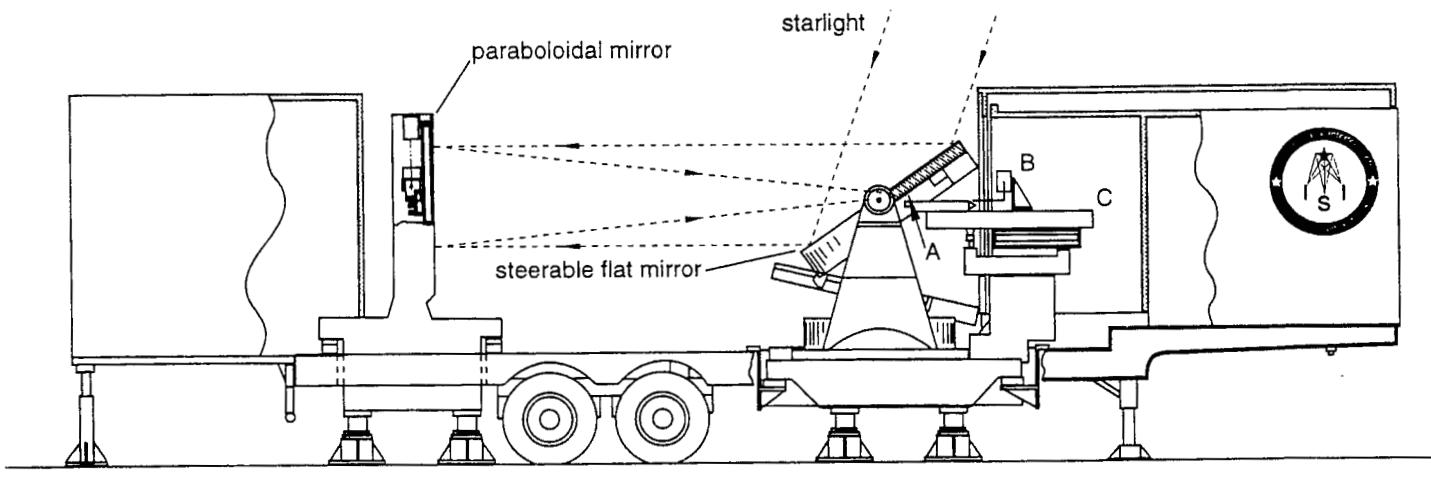
FIG. 2.—The CO(1-0) line profile of IRC +10216. The fitted curve is a flattened parabola (see text).

KNAPP & MORRIS (1985)

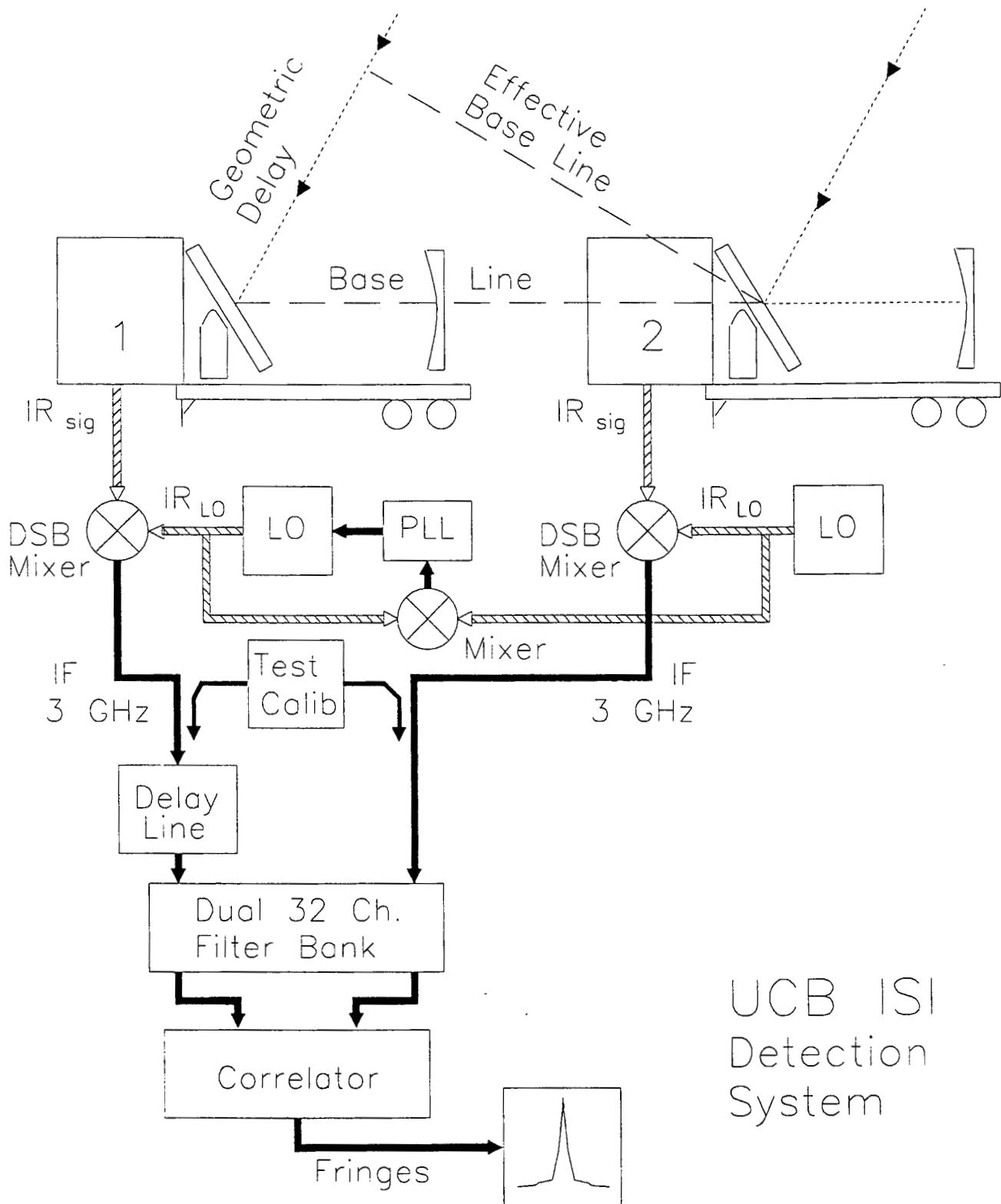
MASS LOSS TRADITIONALLY STUDIED
VIA MOLECULAR TRANSITIONS OF CO
& OTHER MOLECULES, WITH VERY LOW
SPATIAL RESOLUTION, I.E.
ARC SECS → ARC MINS
TIME SCALES → 100's → 1000's OF
MRS.

UKIRT Geballe

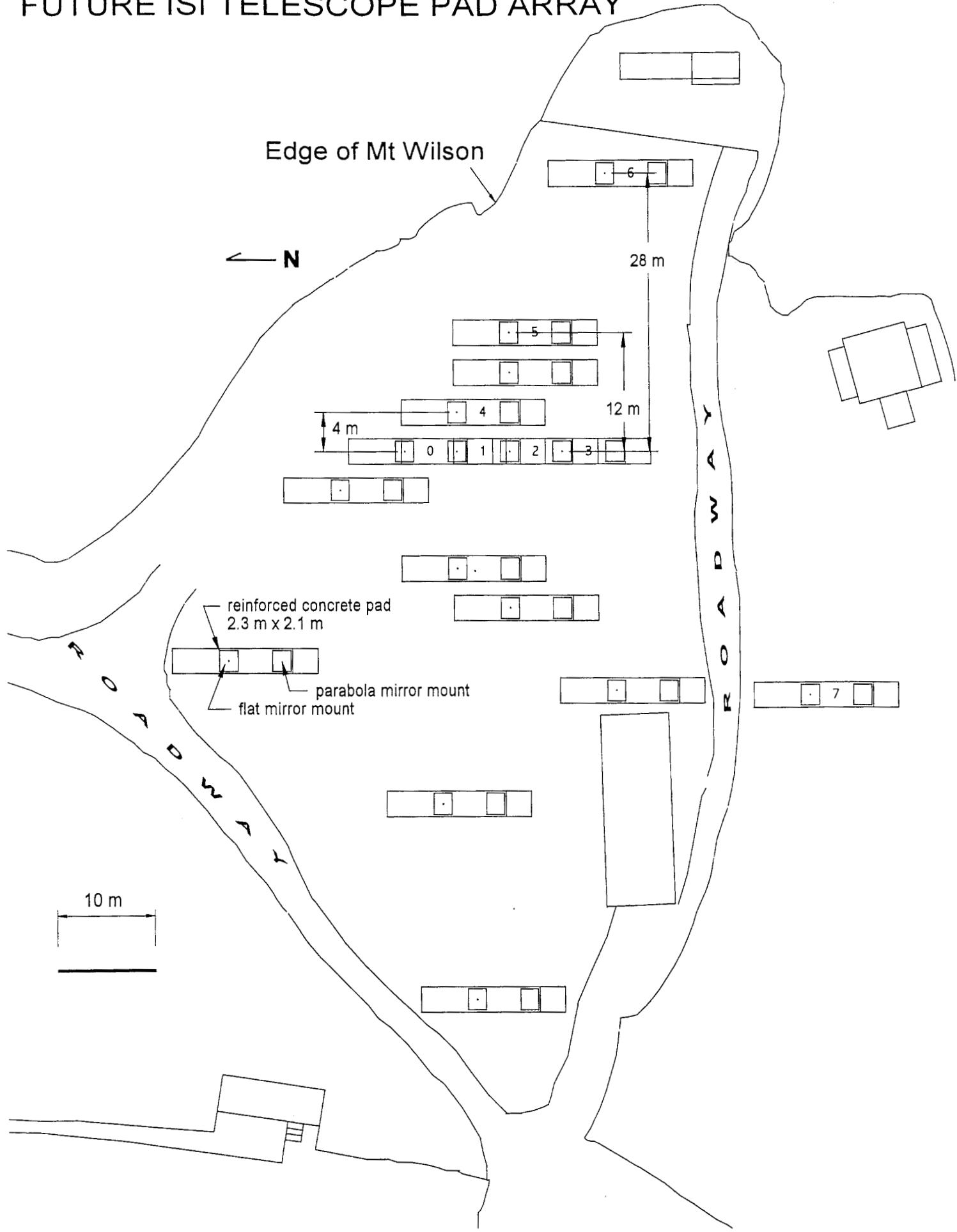


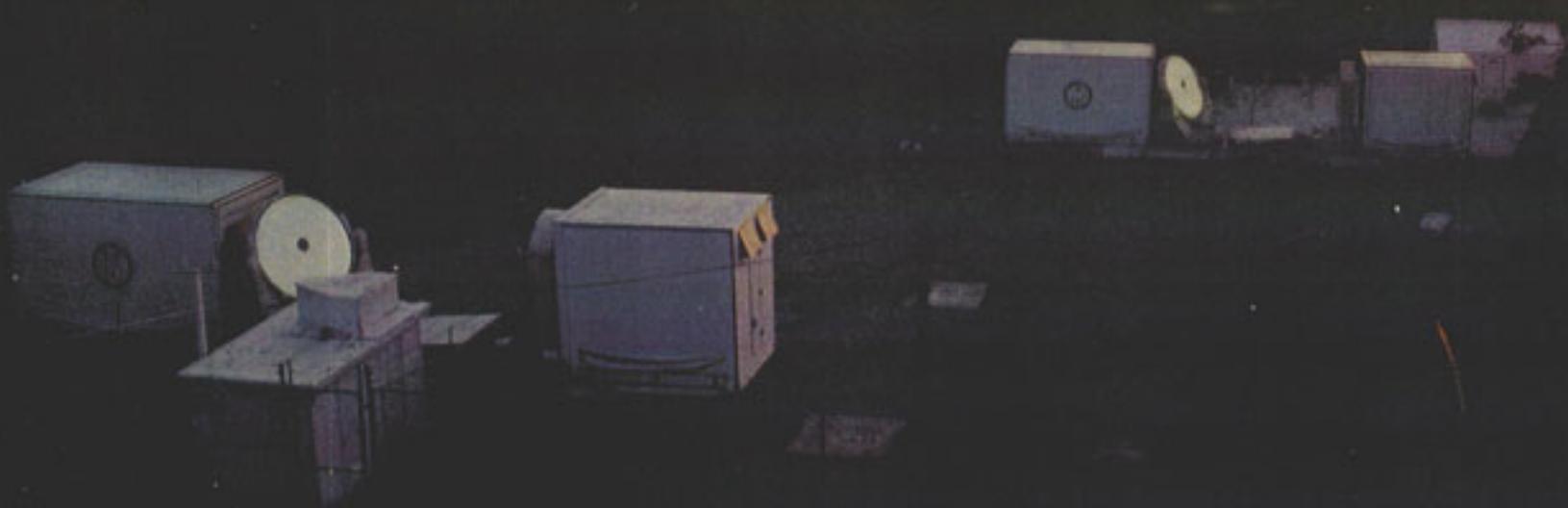


A. Tip-tilt mirror location (mirror not shown)
B. Large Schwarzschild mirror mount
C. Optics table



FUTURE ISI TELESCOPE PAD ARRAY





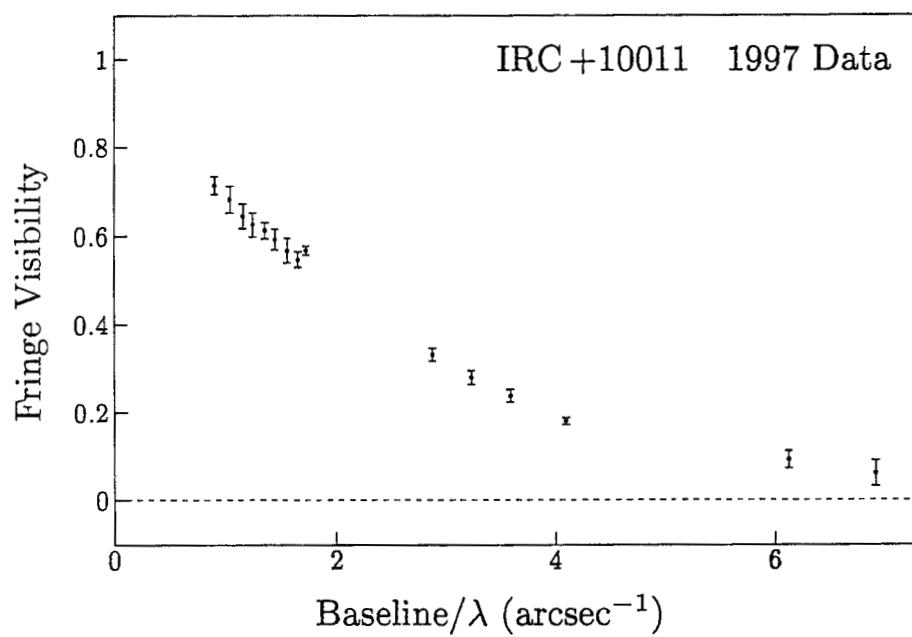
Goals of Observing Program

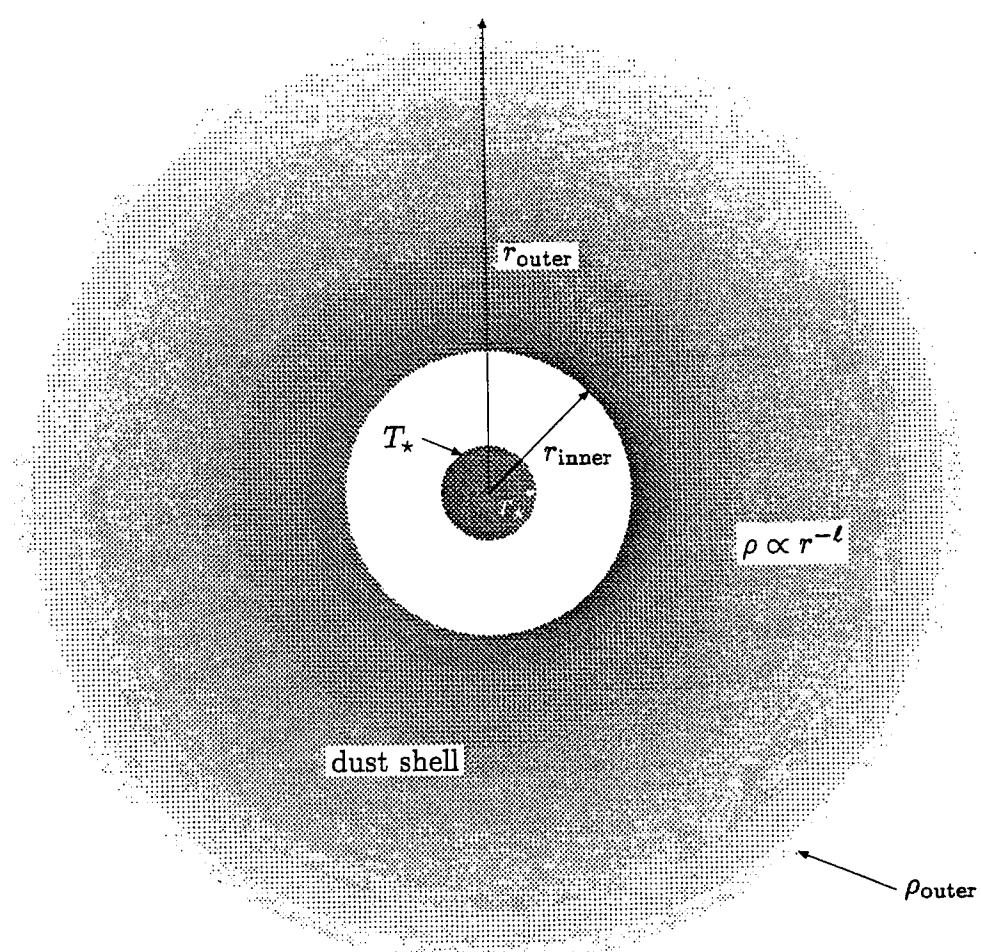
Measure:

- Sizes
- Shapes
- Optical Depths
- Dynamics
- Wavelength Dependence
- Time Evolution
- Spectral lines

Measurements will help us to:

1. Test theories of dust production and mass loss mechanisms
2. Constrain optical properties of dust
3. Better understand stellar evolution on the AGB
4. Spectral lines probe astrochemistry
 - i.e., importance of grains
 - Temperature and density structure of gas/dust envelopes





Modelling Basics:

[Based on work of Wolfire and Cassinelli (1986)]

FULL RADIATIVE TRANSFER CODE:

1. Spherical Code
2. Temperature calculated self consistently
3. Grain size distribution $\sim a^{-3.5}$
4. Grain types: Silicates, Graphite, (AC, BE)
Amorphous Carbon, or Mixtures

YIELDS:

1. Intensity as a function of impact parameter
2. Spectrum

TO COMPARE WITH DATA:

1. Compute Visibility from Intensity Distribution
2. Fit model parameters: Inner radius, Optical depth at 11 microns
3. Constraints are total luminosity and 11 um flux density
4. Also get mid-IR spectrum but don't explicitly fit that.

Model Calculations

Radiative Transfer Equation:

$$\frac{dI_v}{ds} = -\alpha_v I_v + j_v$$

where I_v = specific intensity
 α_v = absorption coefficient
 j_v = emission coefficient

with optical depth $d\tau_v = \alpha_v ds$ or $\tau_v = \int_{s_0}^s \alpha_v ds'$

and source function $S_v = \frac{j_v}{\alpha_v}$ we get:

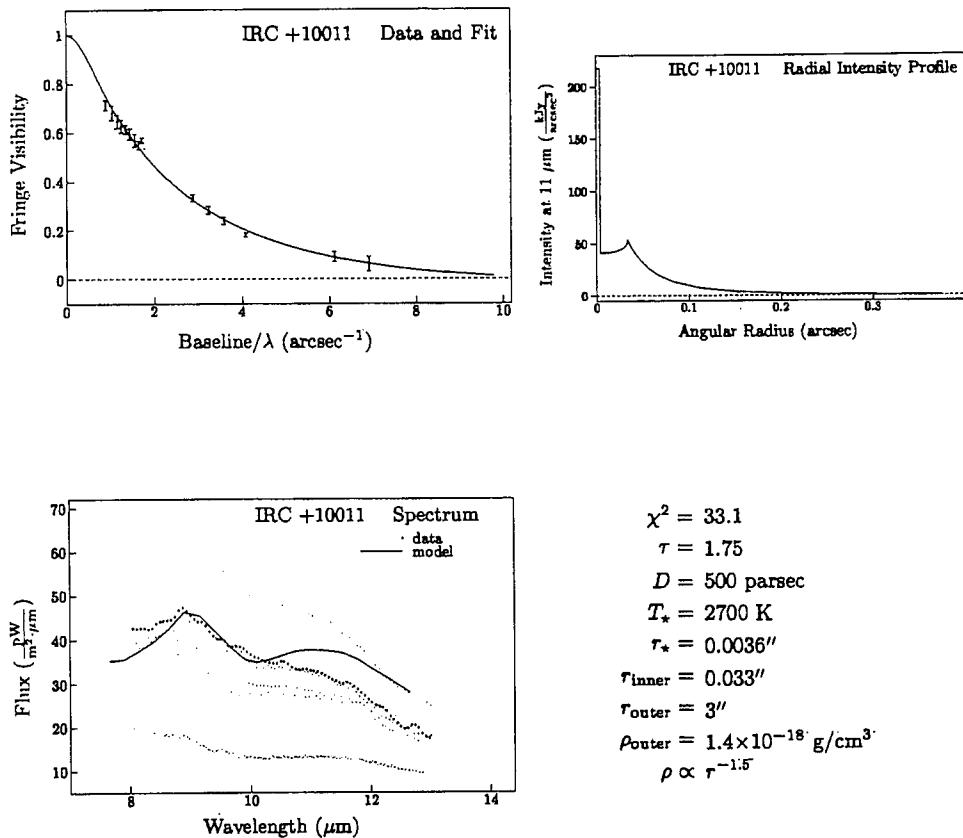
$$I_v(\tau_v) = I_v(0) e^{-\tau_v} + \int_0^{\tau_v} S_v(\tau_v') e^{-(\tau_v - \tau_v')} d\tau_v' \quad (*)$$

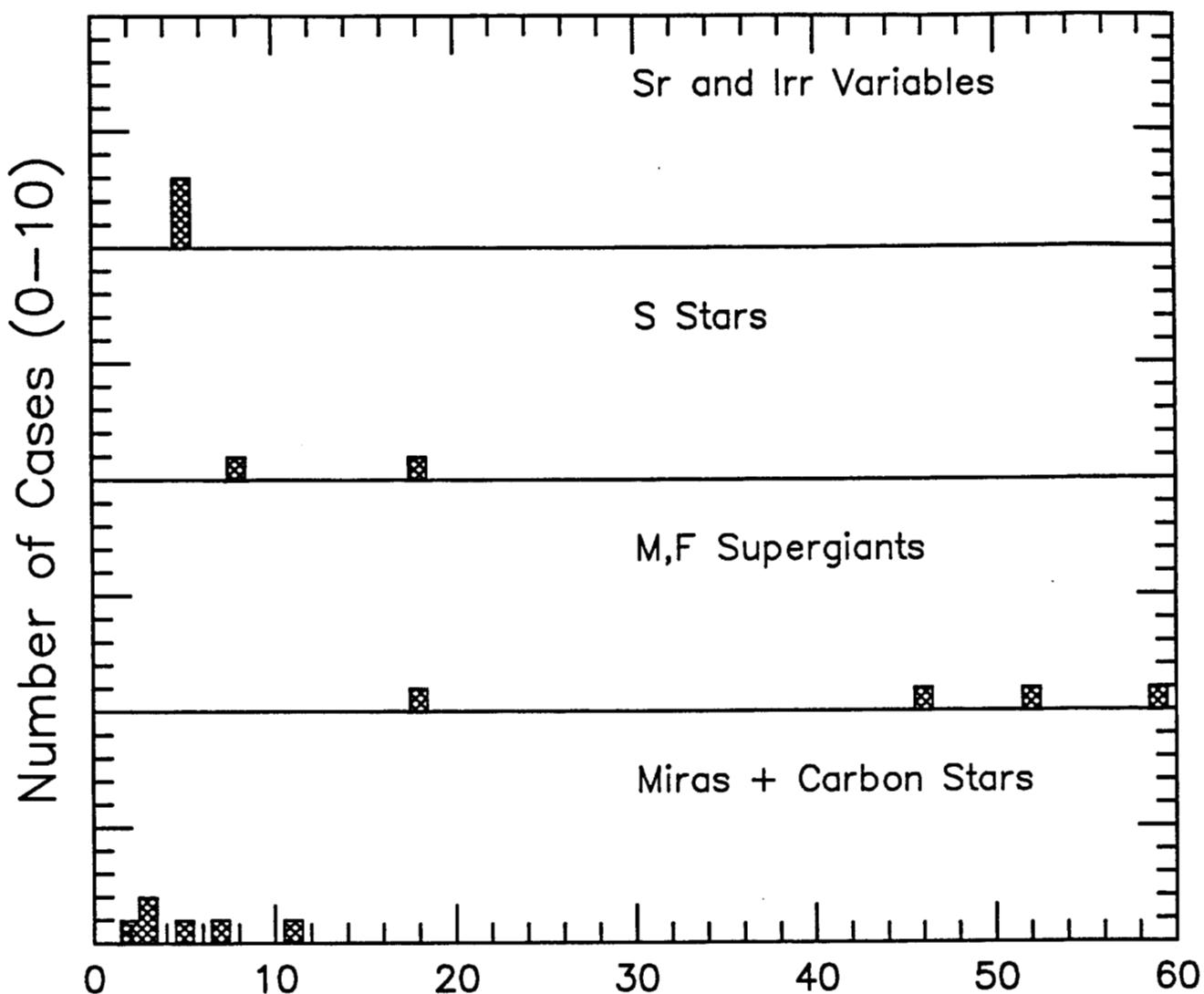
we assume:

- thermal equilibrium ($\rightarrow S_v = B_v(T)$)
- spherical symmetry
- temperature profile $T \propto r^{-\alpha}$ ($\alpha = 0.4$)
- density profile of dust $\rho \propto r^{-\beta}$ ($\beta = 2$)

by integrating (*) for each ray and calculating the Fourier Transform one gets the **visibility**

comparison with our observations \rightarrow temperature and radius of dust shell





Inner Radii of Dust Shells [R_{in}/R_*]

BESTER & DANCHI
(1995)

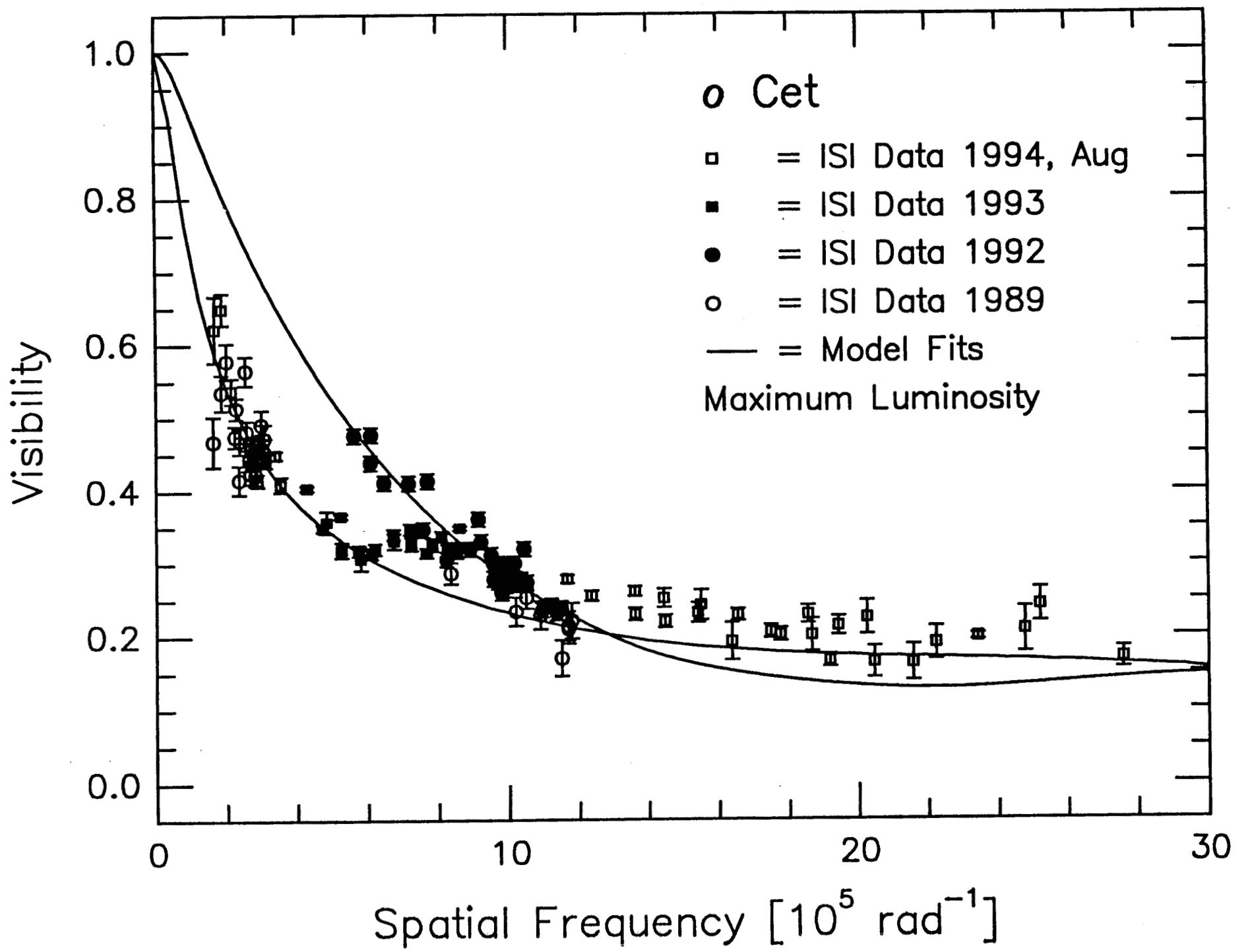
ASTRO. & SPACE SCIENCES.

224 , 339 .

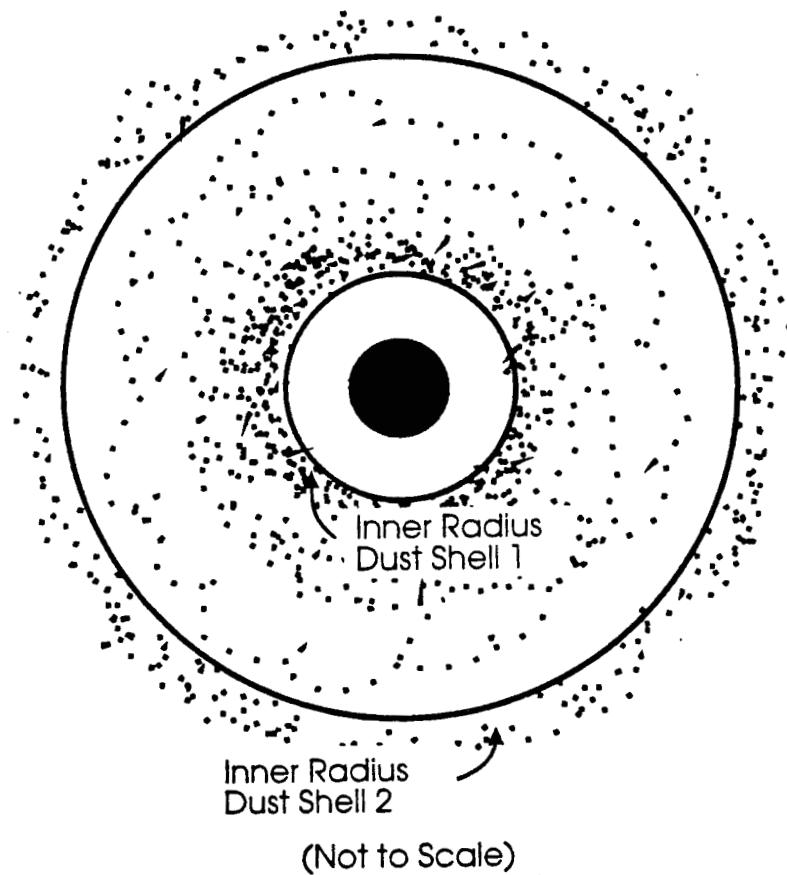
CONCLUSIONS:

- 1. Inner radii within a few stellar radii for Miras and Carbon stars.**
- 2. Wider variation for other spectral types**
- 3. Implies if dust always forms close to star, time scale for dust emission varies depending on spectral class**
- 4. Atmospheric scale height for VX Sgr in rough agreement with theory**
- 5. Diameters at 11 um consistent with optical diameters for supergiants Alpha Orionis and Alpha Scorpii.**
- 6. Alpha Orionis had a recent burst of dust formation.**
- 7. Dust is created and destroyed in complex environment of Omicron Ceti.**
- 8. Complex dust patterns exist for NML Tau and NML Cyg, not simple uniform outflows**
- 9. MANY INTERESTING RESULTS AND MORE TO COME!!!**

LONG BASELINE INTERFEROMETRY IN THE MID-IR HAS ALREADY PRODUCED IMPORTANT RESULTS AND HAS GREAT POTENTIAL FOR THE FUTURE.



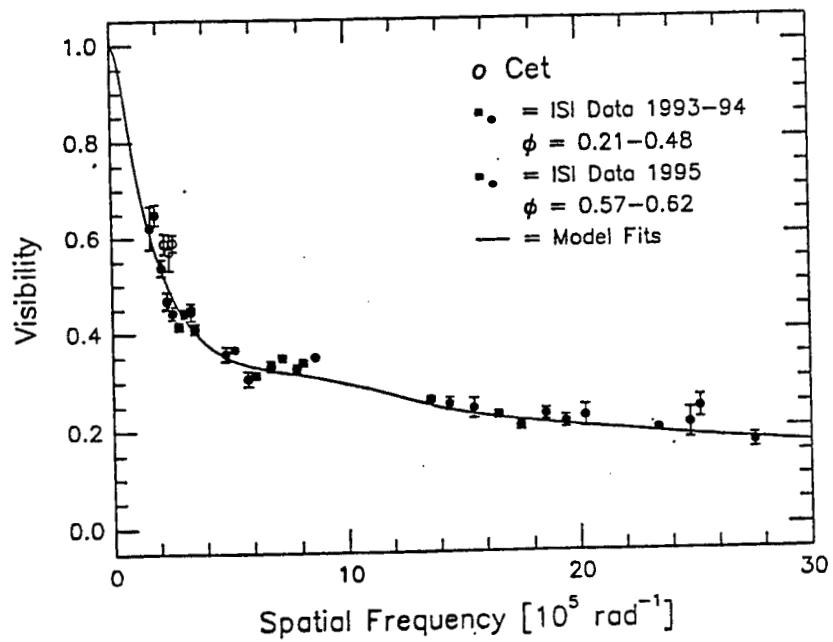
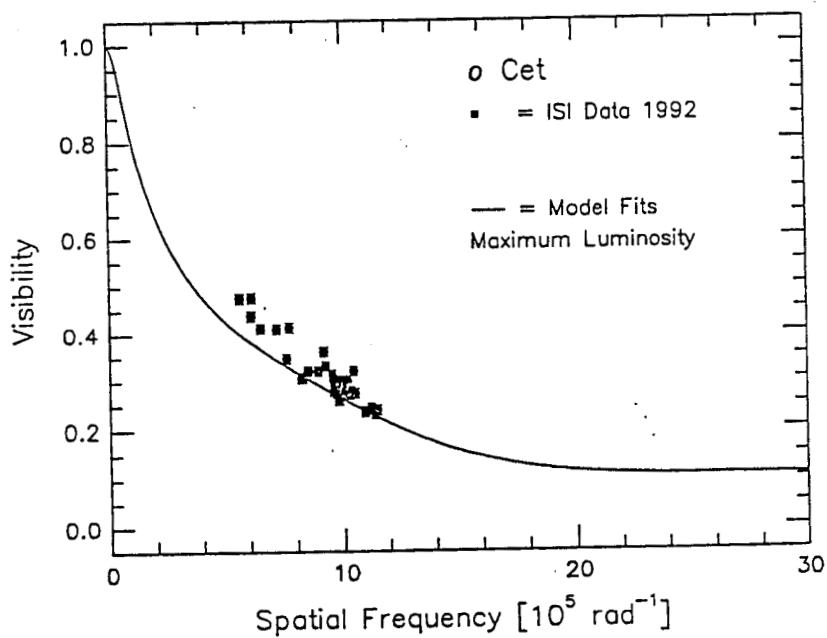
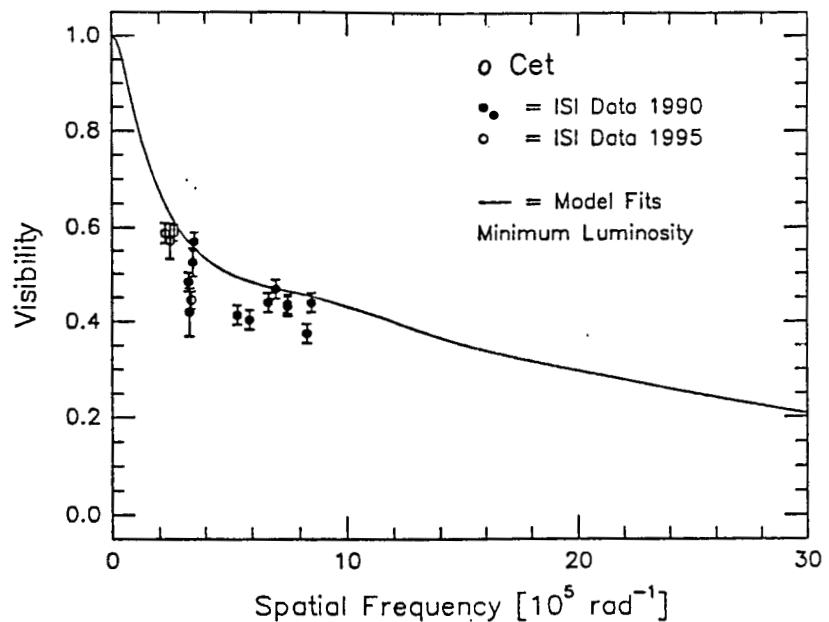
TWO DUST SHELLS MODEL

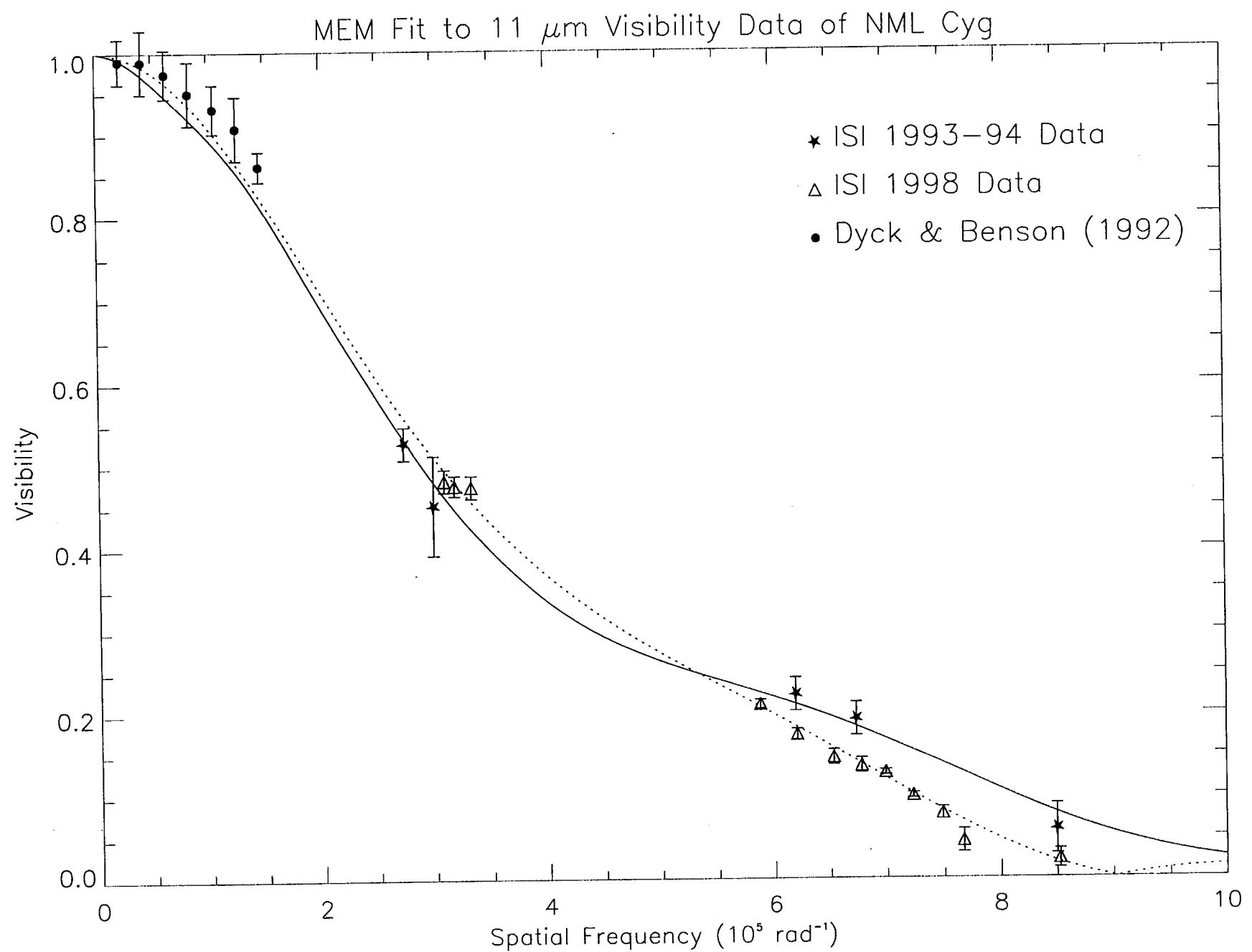


(Not to Scale)

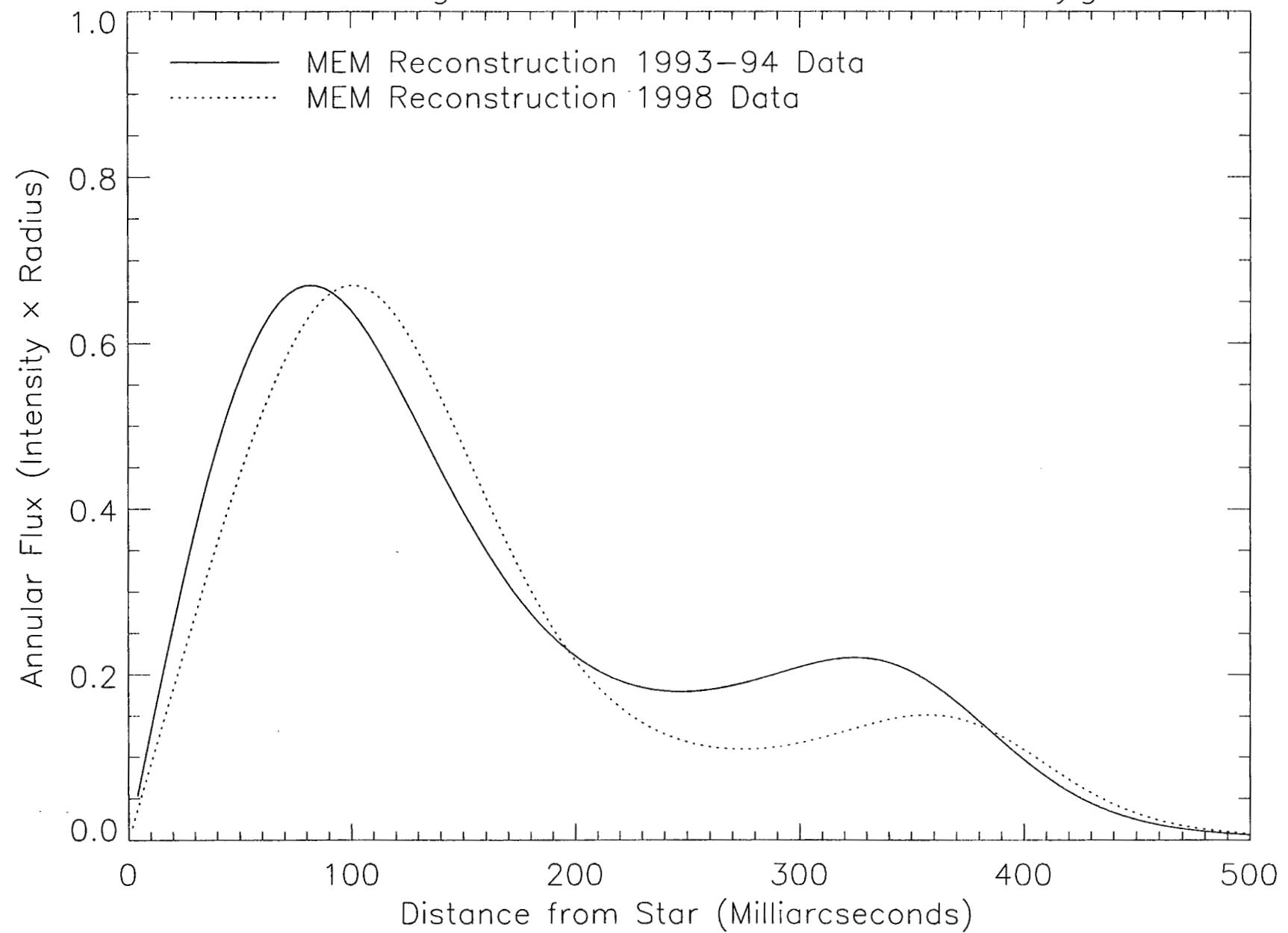
Lopez et al.

Figure 6





MEM Brightness Distributions for NML Cyg



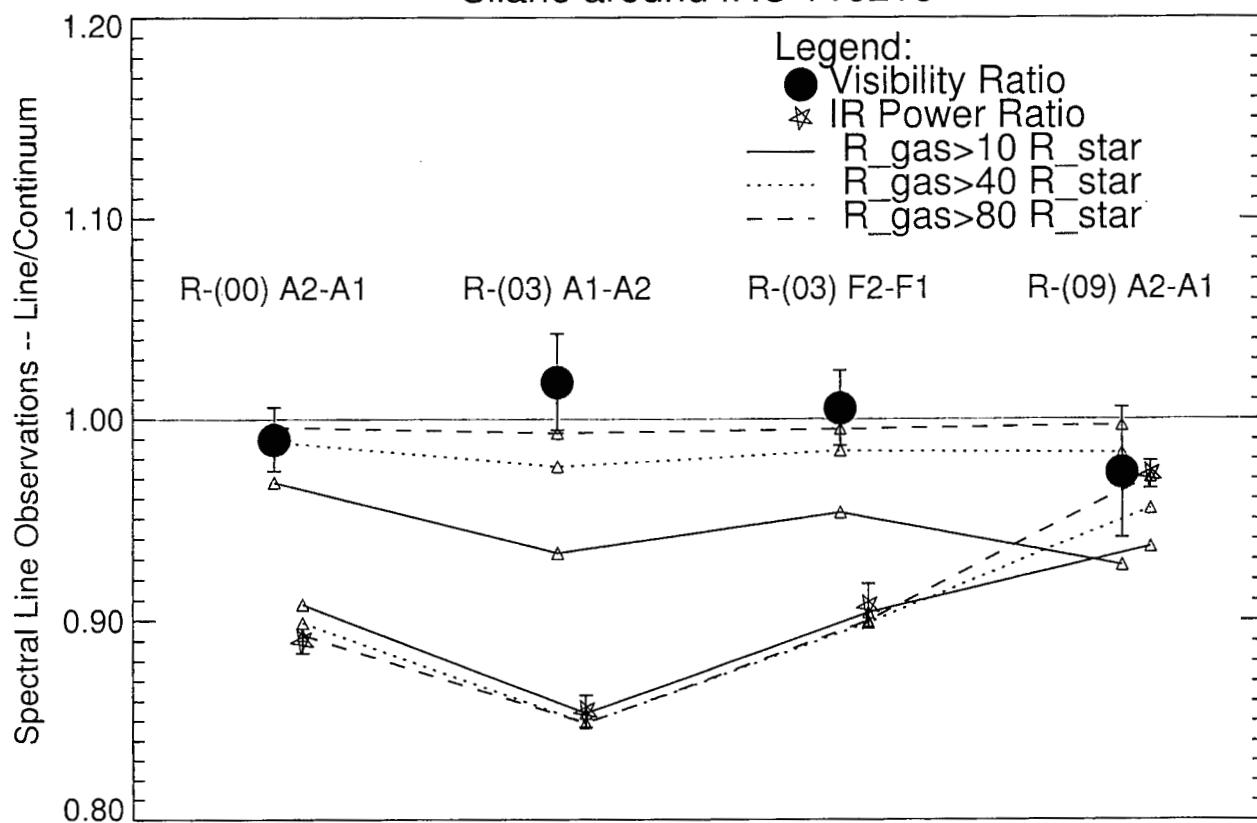
High angular resolution on spectral lines:

- Study distribution of gas and dust separately
- High spatial and spectral resolution simultaneously
- Molecules:
 NH_3 , SiH_4 , C_2H_4 in various excited states
- Sources:
IRC +10216, VY CMa, NML Cyg, NML Tau,
IRC +10011, IRC +10420, R Leo, α Her

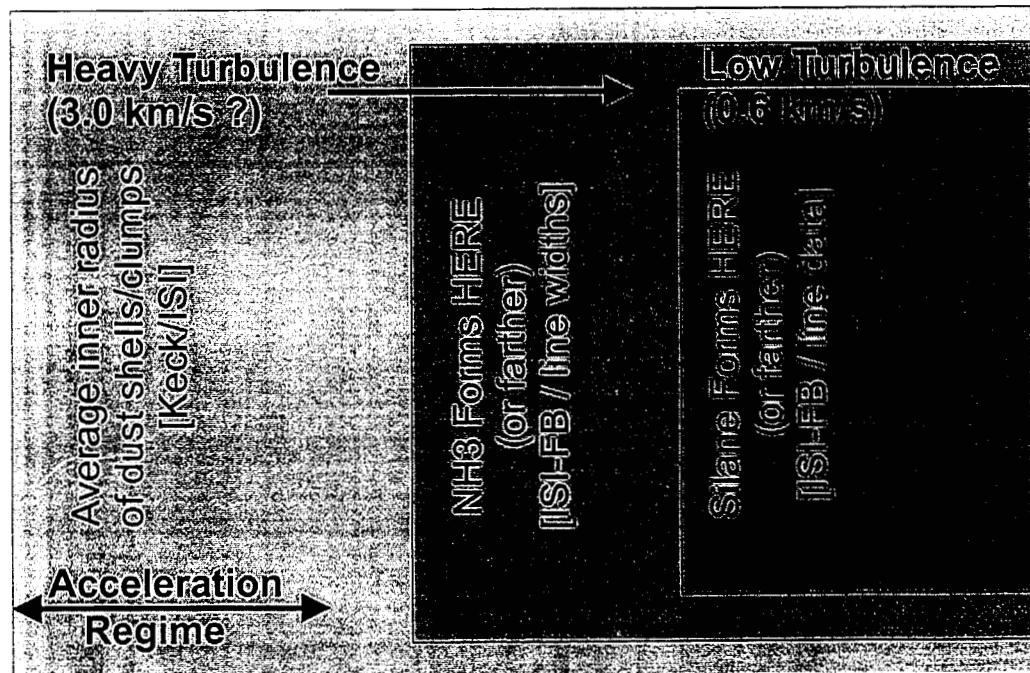
Problems:

- Find CO_2 local oscillator lines close by using various isotopes like ^{12}C , ^{13}C , ^{14}C , ^{16}O , ^{18}O
- Take into account LSR velocity of the source
- Need a more complex correlator

Silane around IRC +10216



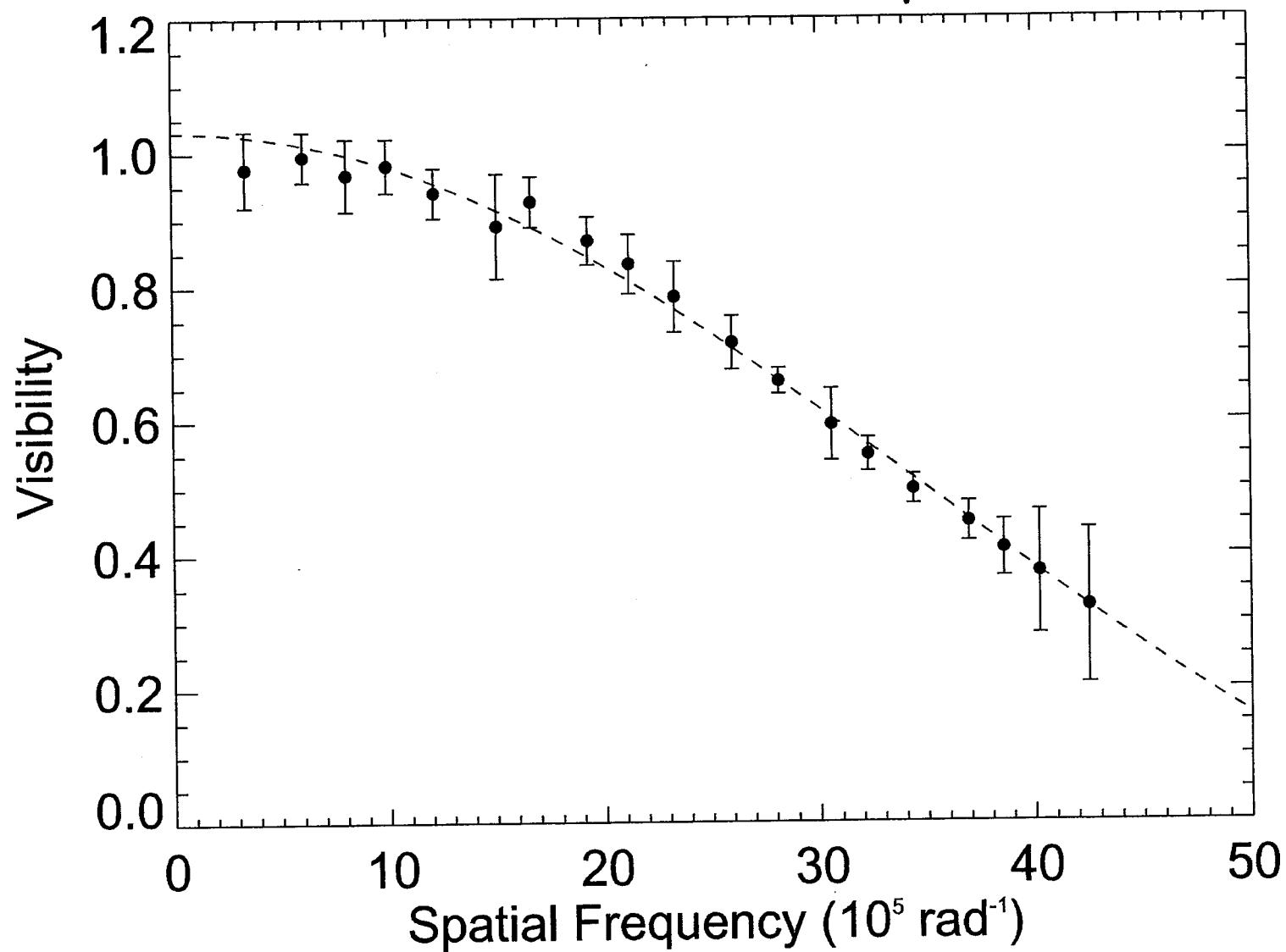
Circumstellar Envelope of IRC +10216



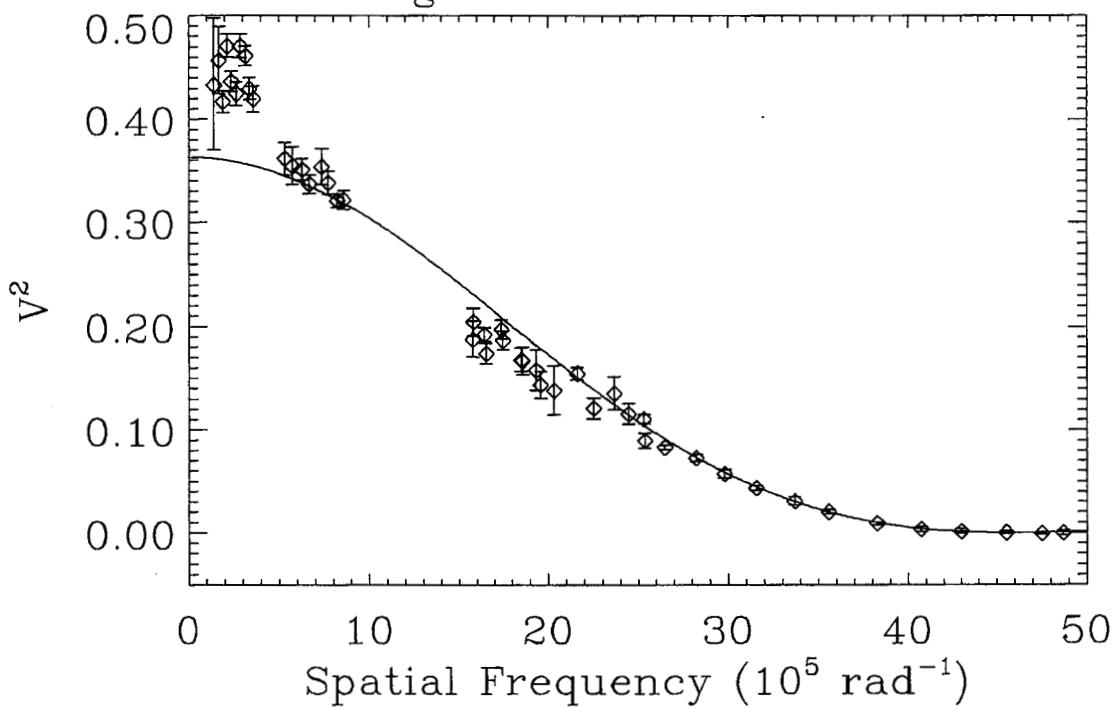
$1 R^*$	$3 R^*$	$6.8 R^*$	$10 R^*$	$40 R^*$	$80 R^*$
22 mas	66 mas	150 mas	220 mas	$0''.9$	$1''.8$

42.6 ± 1.9 mas

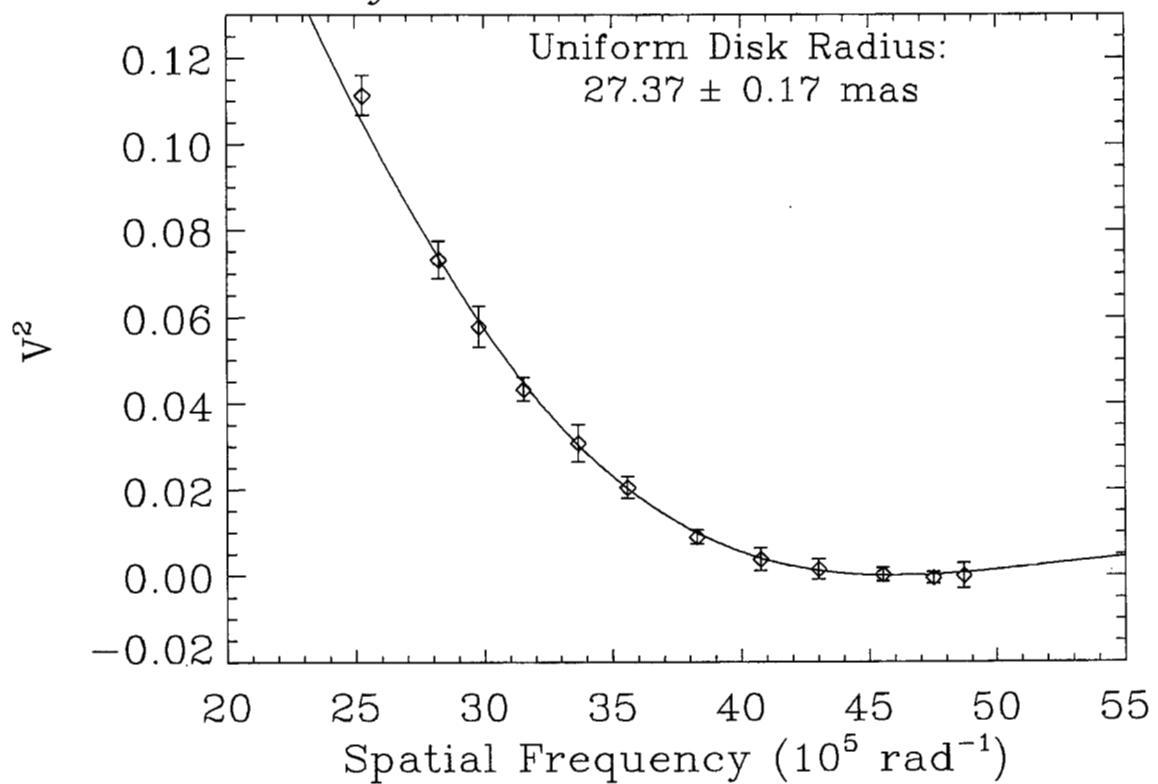
α Orionis at 2.25 μ m



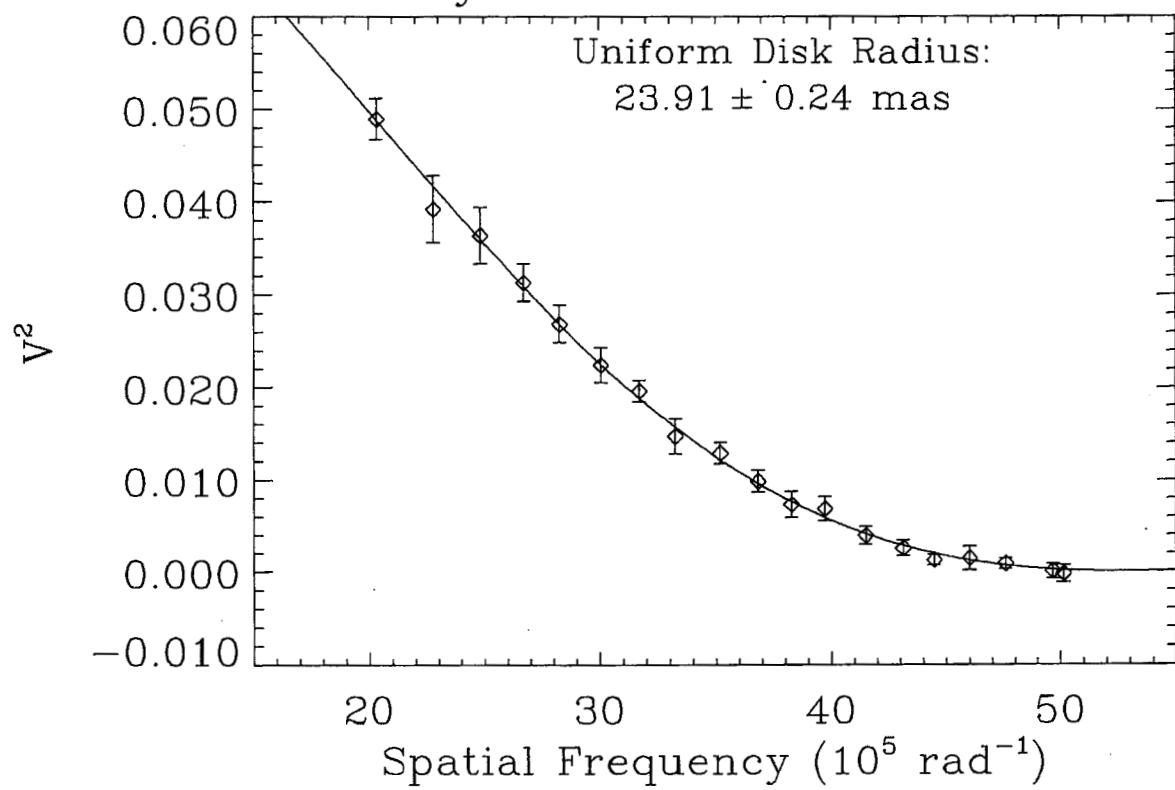
Visibility Measurements of α Orionis
Including Data from 1993 and 1994

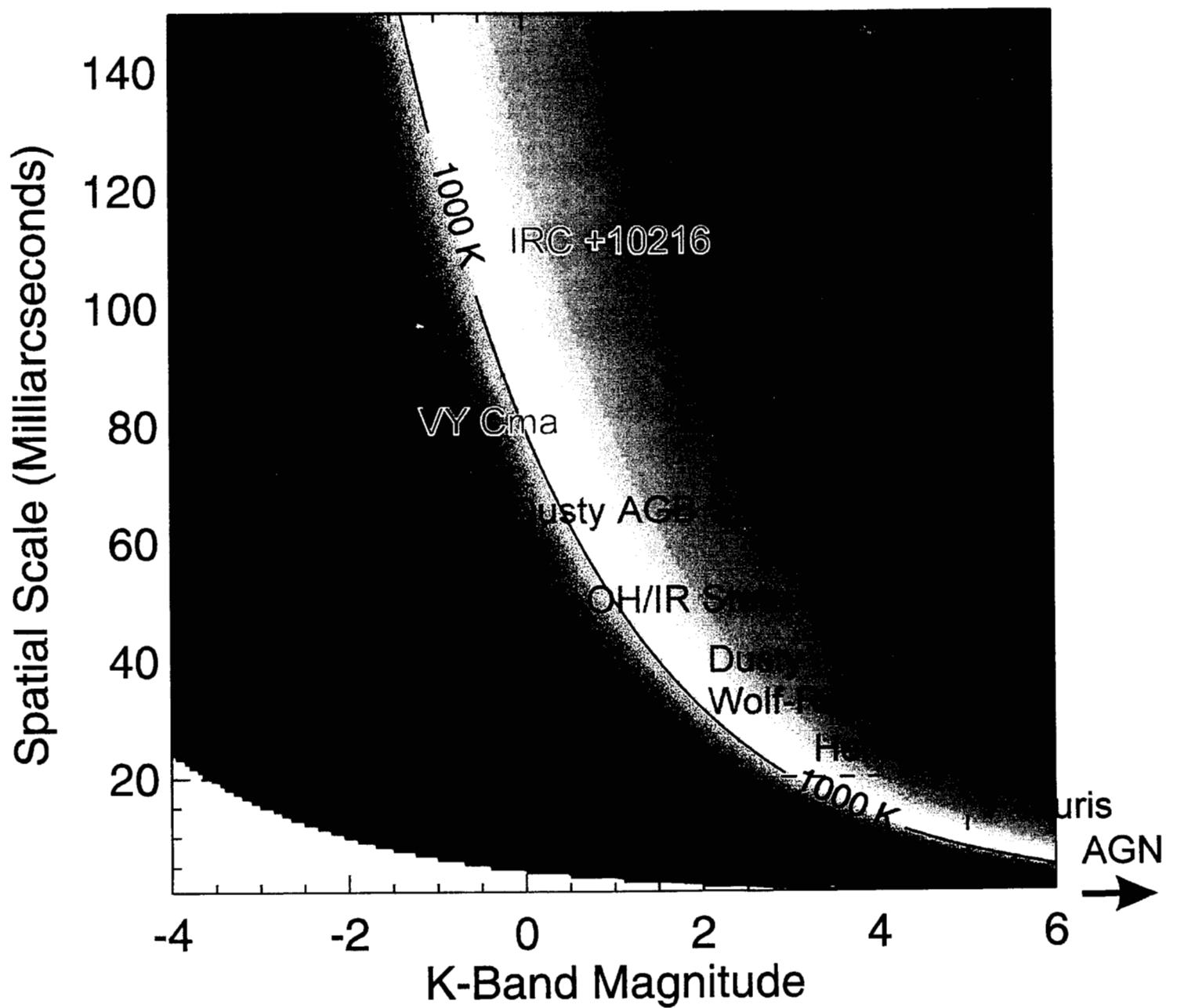


Visibility Measurements of α Orionis



Visibility Measurements of α Ceti





Aperture Masking at Keck

Results and Science Potential

- Highest resolution images of circumstellar envelopes available
- Spiral dust shells discovered around Wolf-Rayet stars – colliding winds?
- Multi-wavelength diameter measurements to probe the atmospheric structures of Miras and Red Supergiants
- Circumstellar disks around Young Stellar Objects (YSOs) can be resolved for the first time
- Highly asymmetric flows around prototypical dusty AGB stars insist on new mass-loss mechanisms – or at least new twists on the old
- Proper motion studies in infancy, could be key to understanding these complicated envelopes
- In general, these observations offer an important data set to view in context of high resolution visible data (stellar hotspots) and radio/mm observations (SiO and H₂O masers)

α ORI APERTURE MASKING,
 $(T_c D)$ 710 nm

372 R. W. Wilson et al.

Table 2. Uniform disc and point-source parameters for Betelgeuse.

Wavelength (nm)	Disk Diameter (mas)	Point source parameters		
		Flux (percent of total)	Radius from center (mas)	PA (degrees)
546	57(+/-2)	10(+/-3)	9(+/-1)	101(+/-3)
		10(+/-3)	4(+/-5)	285(+/-10)
633	55(+/-1)	14(+/-2)	8(+/-2)	98(+/-5)
		11(+/-2)	8(+/-5)	300(+/-3)
700	49(+/-3)	10(+/-3)	8(+/-1)	105(+/-3)
		10(+/-3)	8(+/-1)	302(+/-3)
710	54(+/-2)	12(+/-2)	9(+/-2)	105(+/-3)
		11(+/-2)	9(+/-2)	305(+/-4)

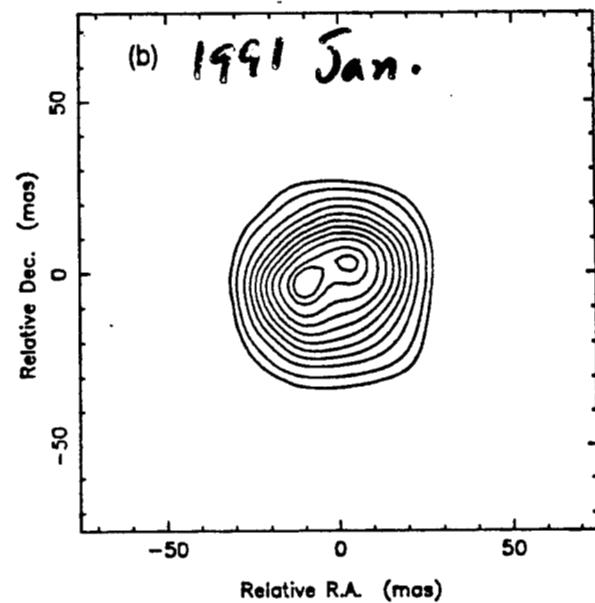
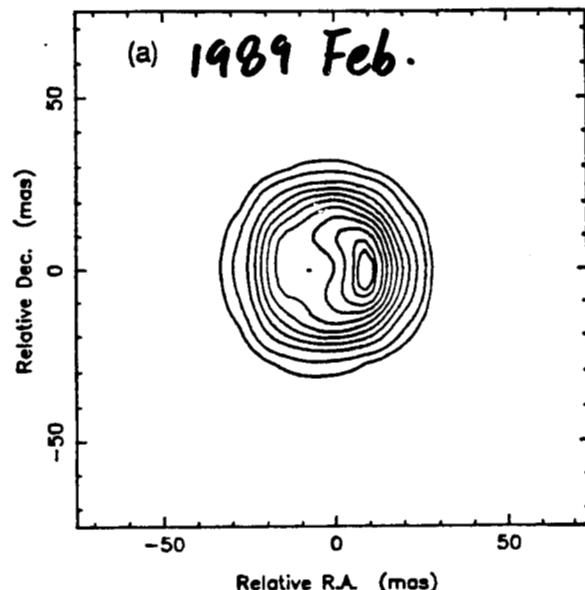
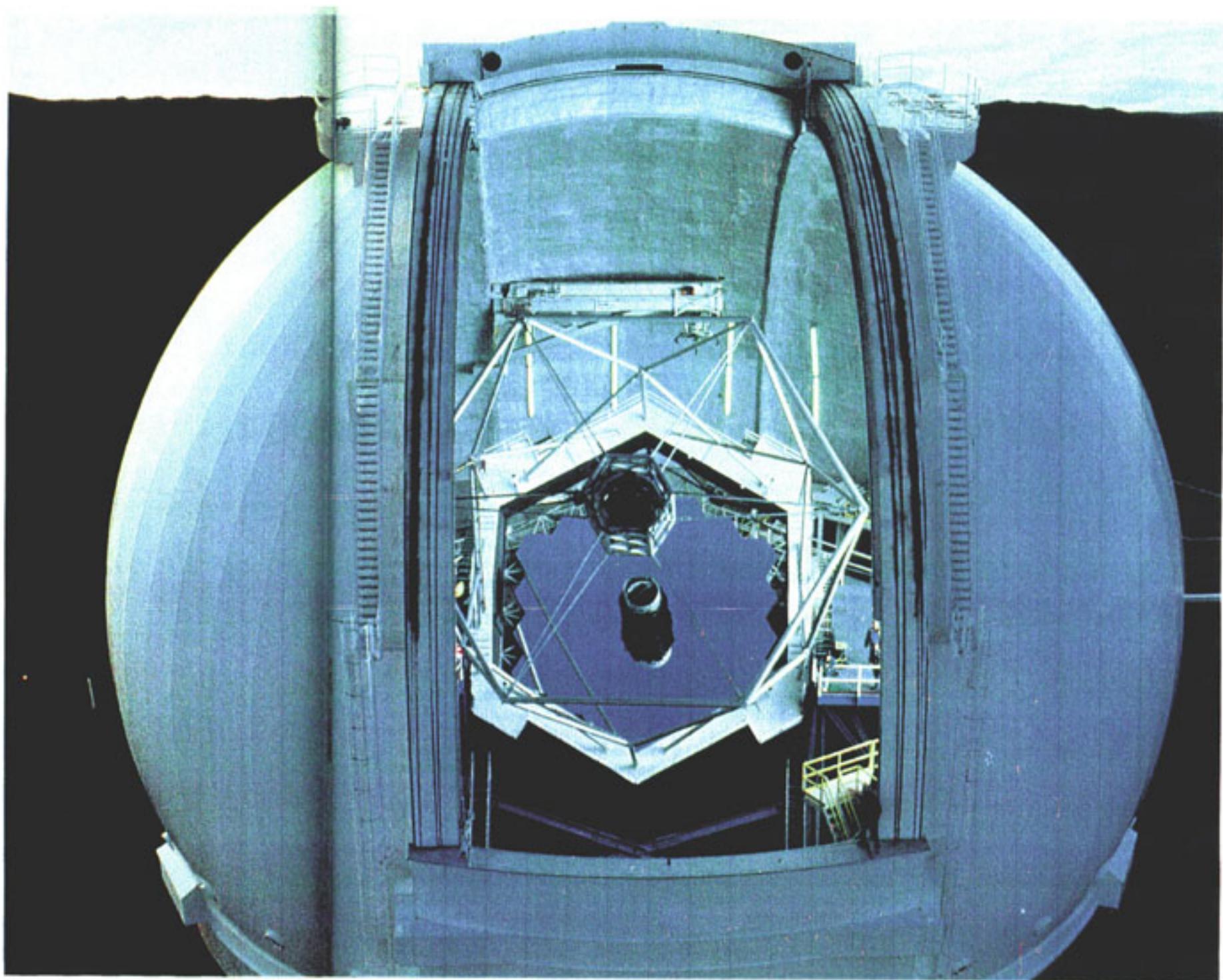


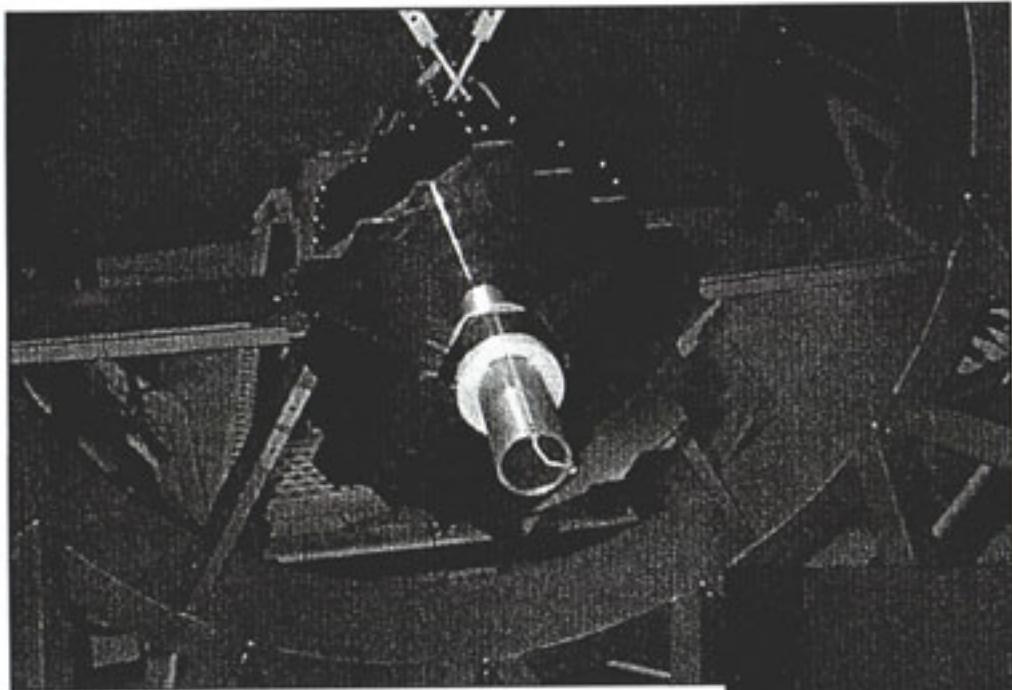
Figure 4. MEM reconstructions of Betelgeuse at 710 nm in (a) 1989 February, and (b) 1991 January. Contours are 5, 10, 20,..., 90, 95 per cent of the peak intensity.

ES

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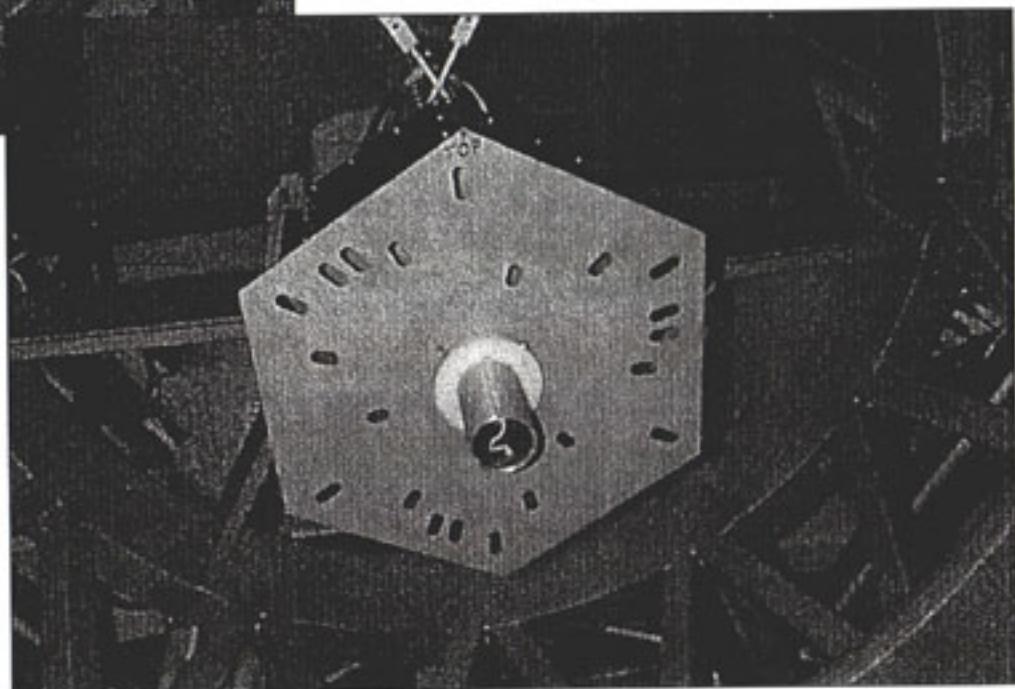
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aire travailler

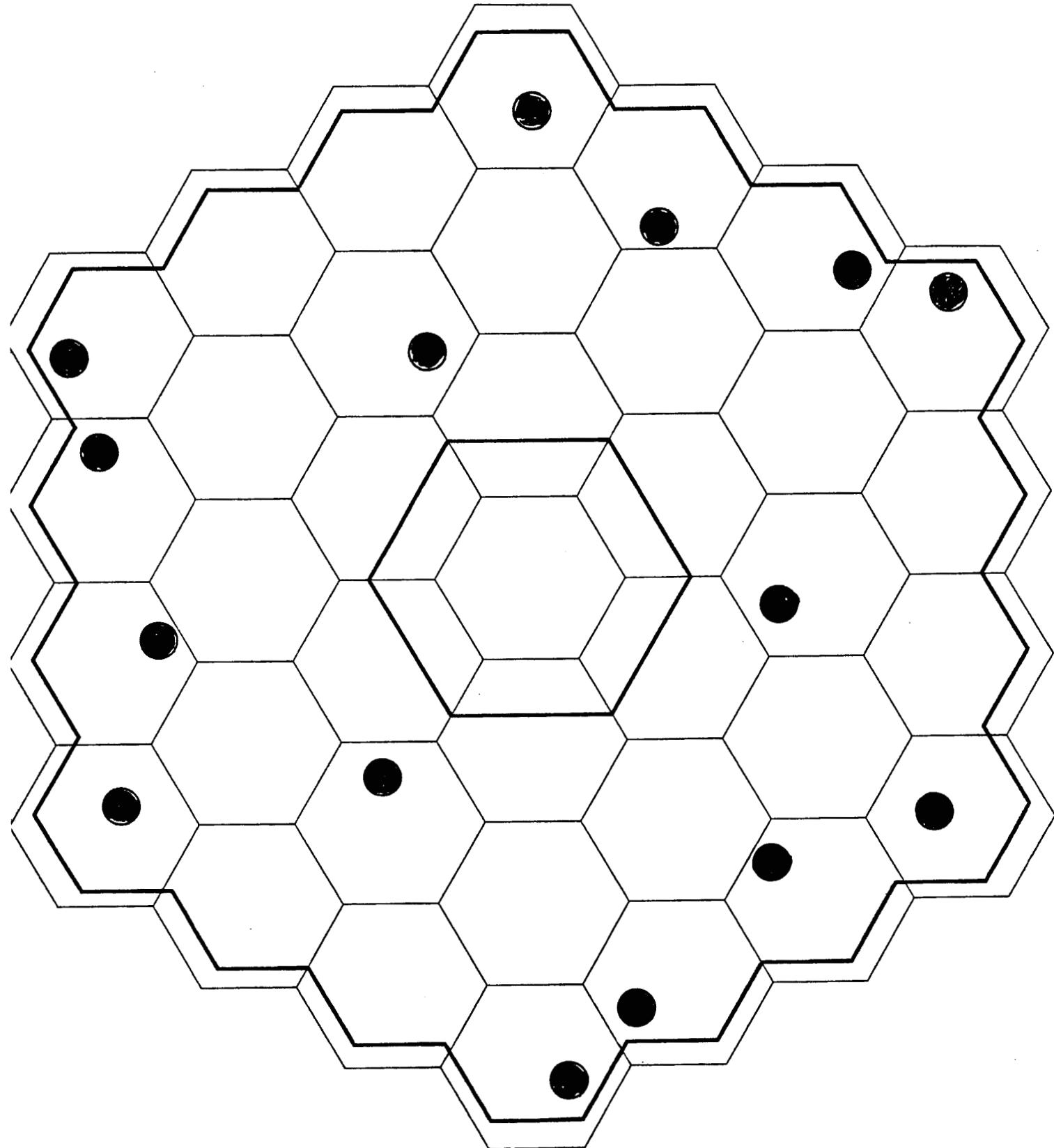




IR Secondary Mirror of
Keck I Telescope, with
Aperture Masking support
stalk installed.

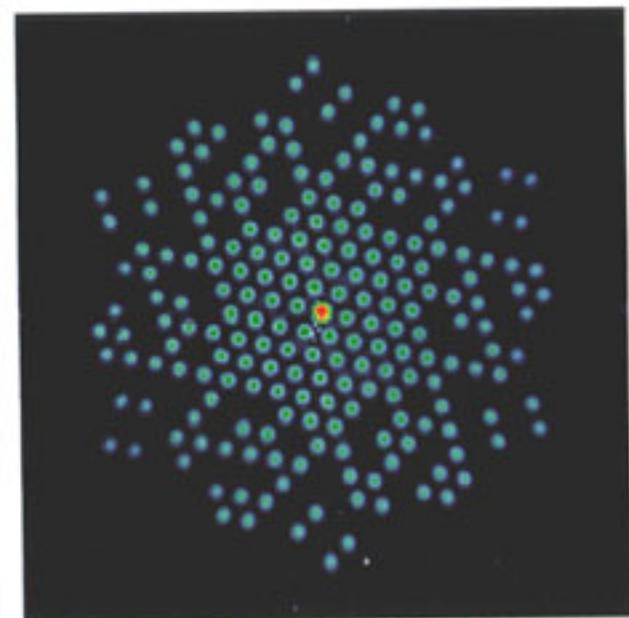
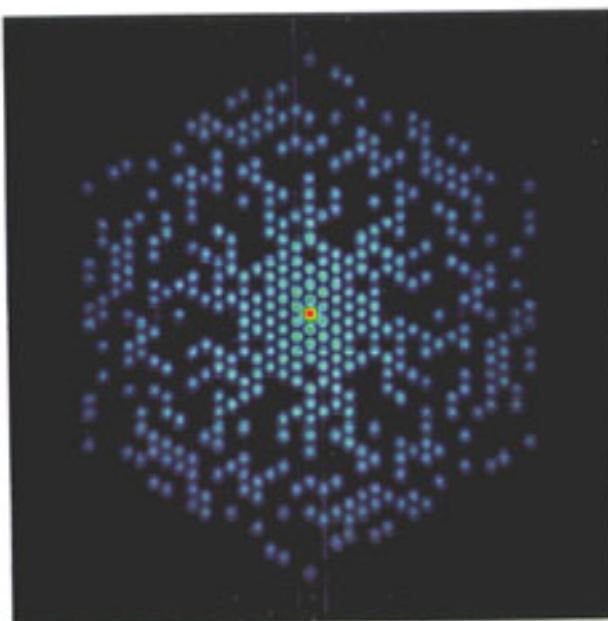
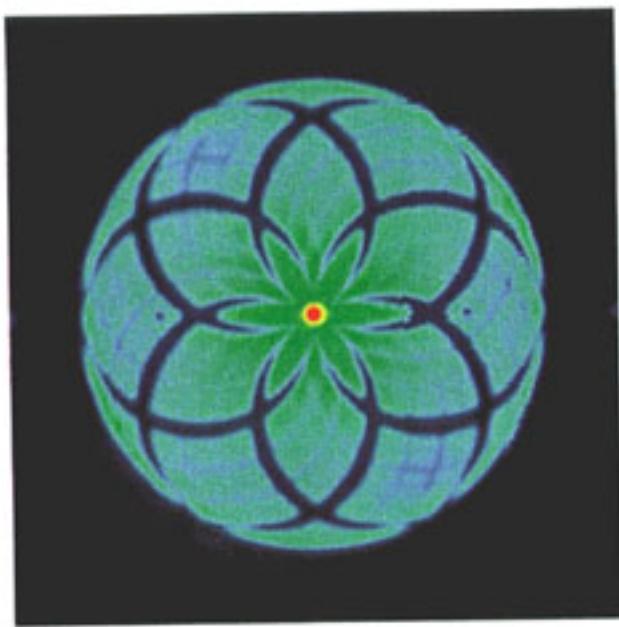
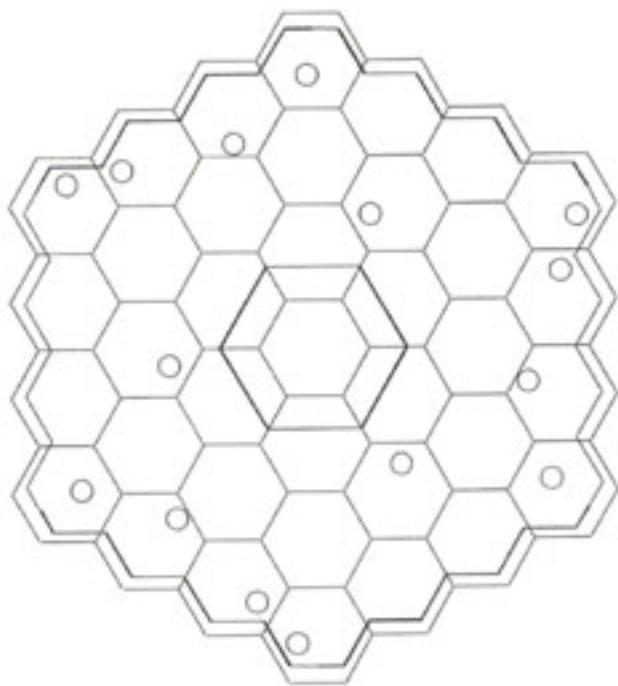
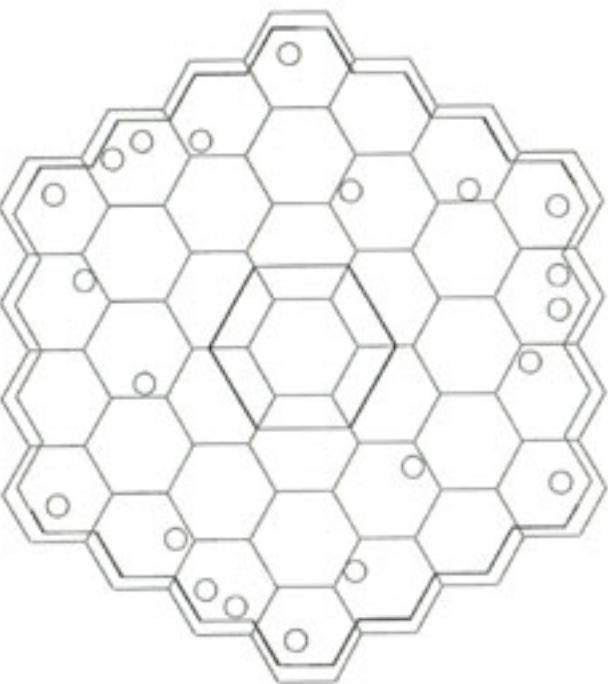
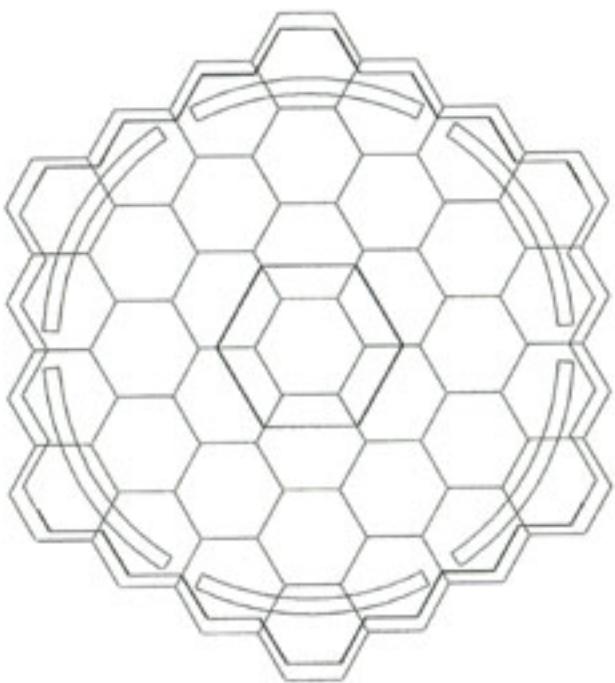
IR Secondary with 21
Hole Golay Aperture
Mask installed on support
stalk. Note collars
prevent mask from falling
off and from touching
secondary mirror.

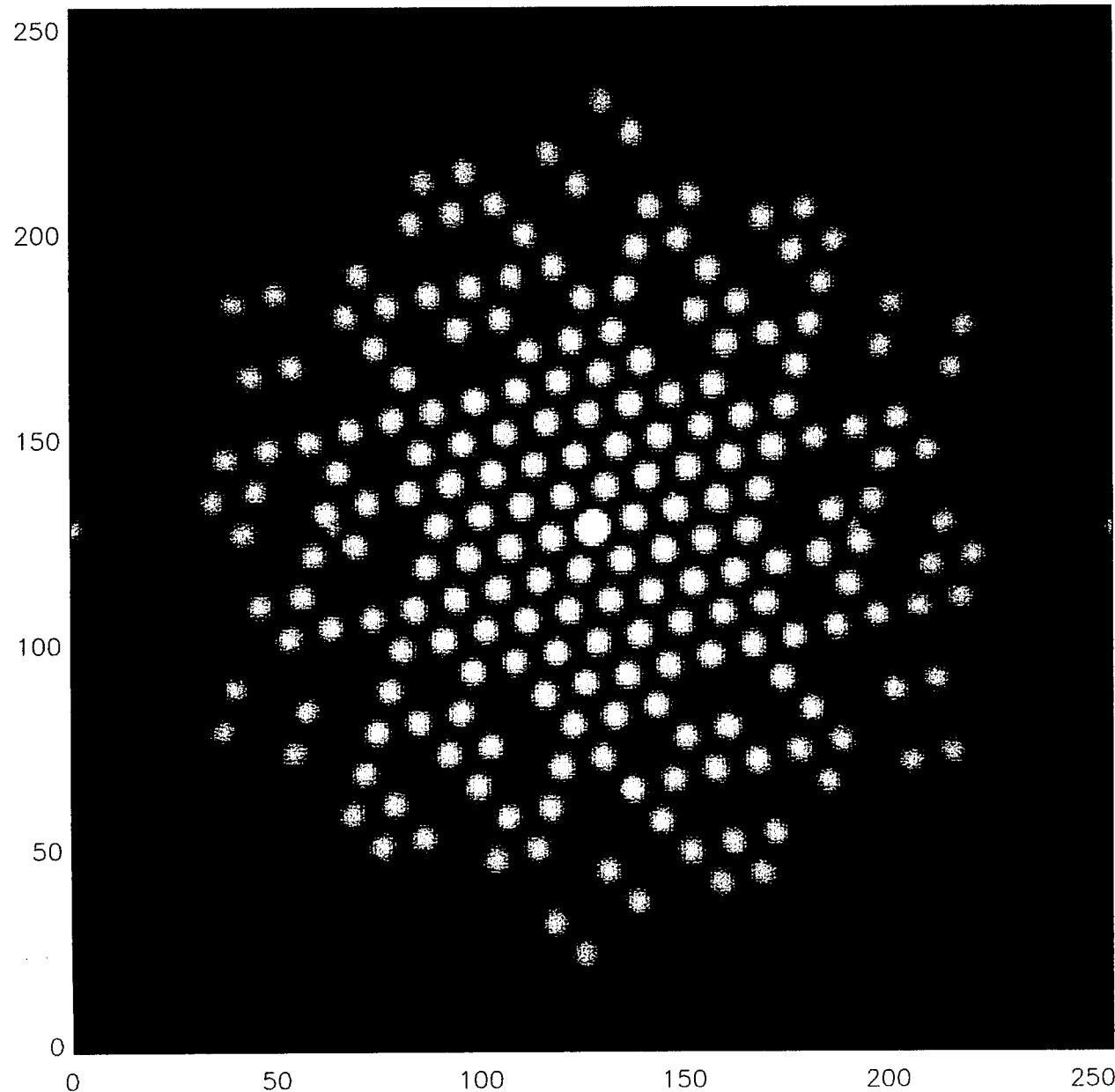




Keck Pupil Mask

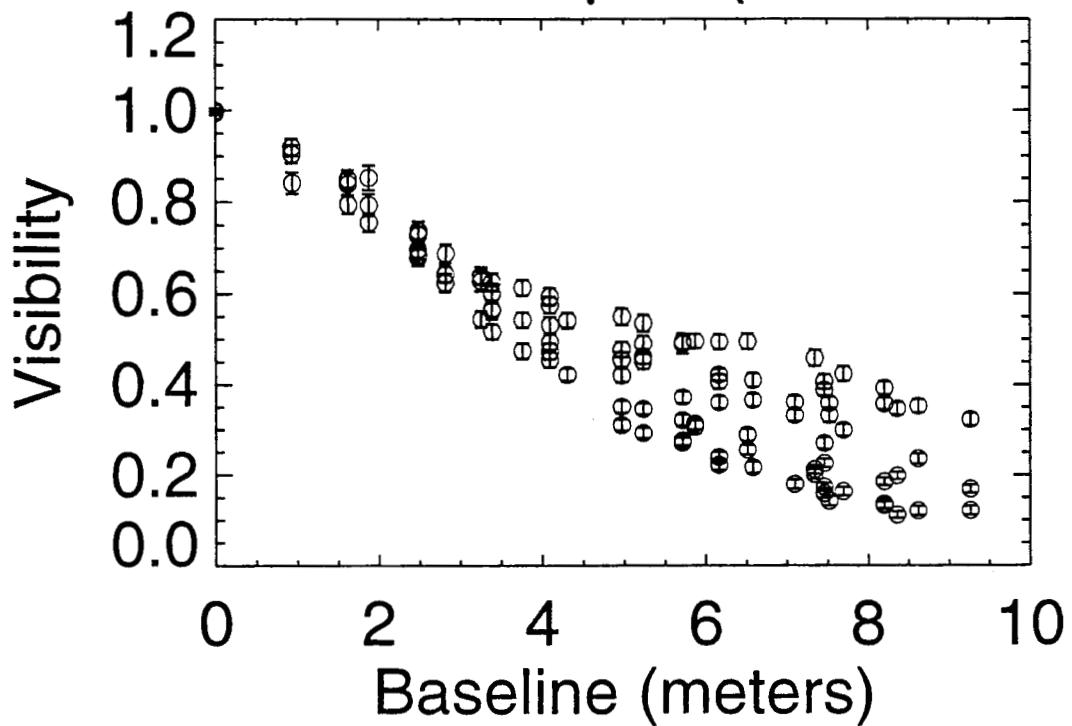
DRAWN BY:	Peter Tuthill	DATE:	25-Feb-97
SCALE:	1:50	MATERIAL:	Aluminum
15 Hole Golay (35cm holes)			



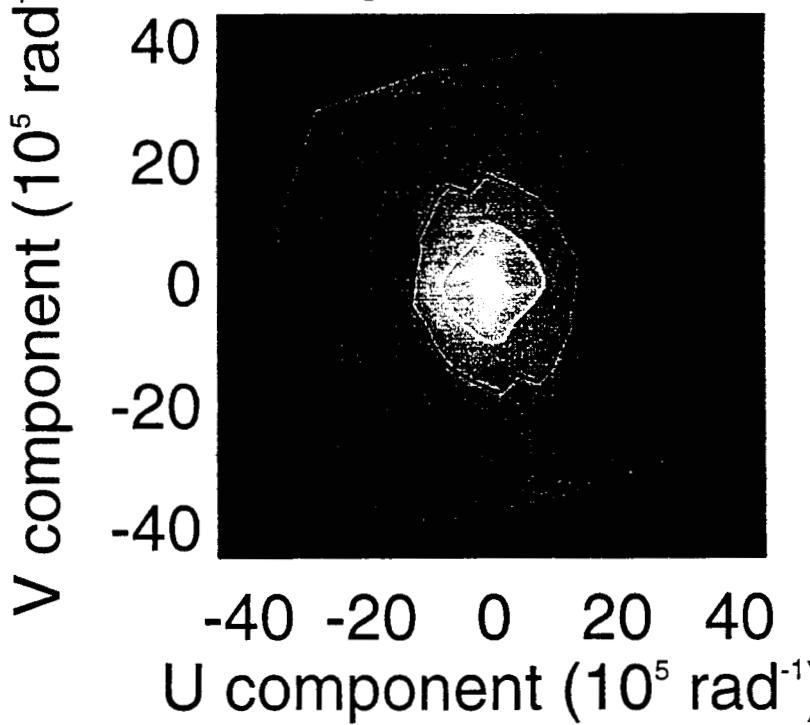


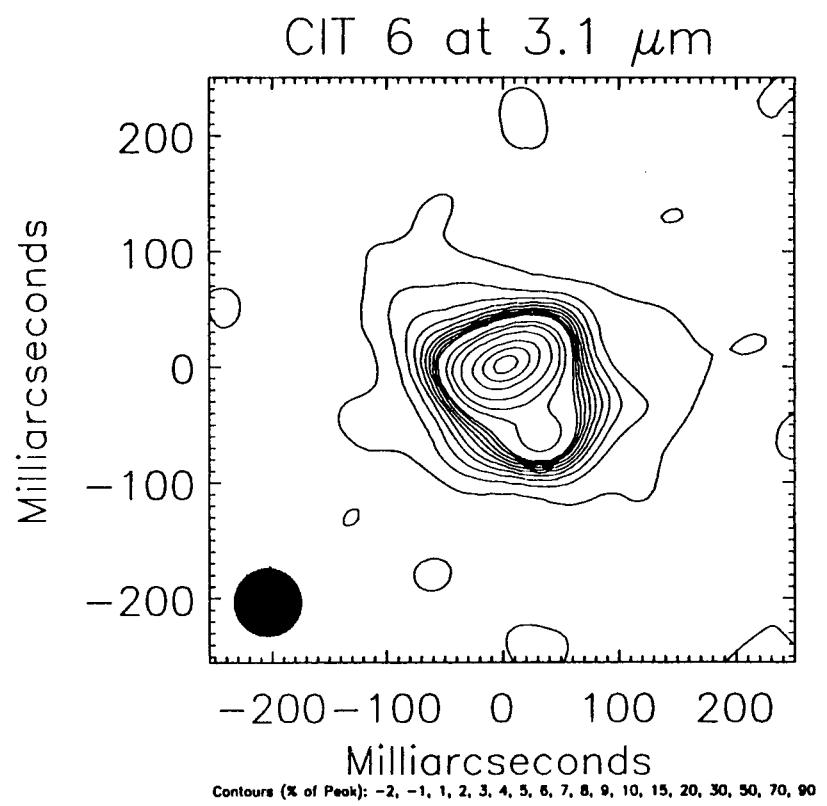
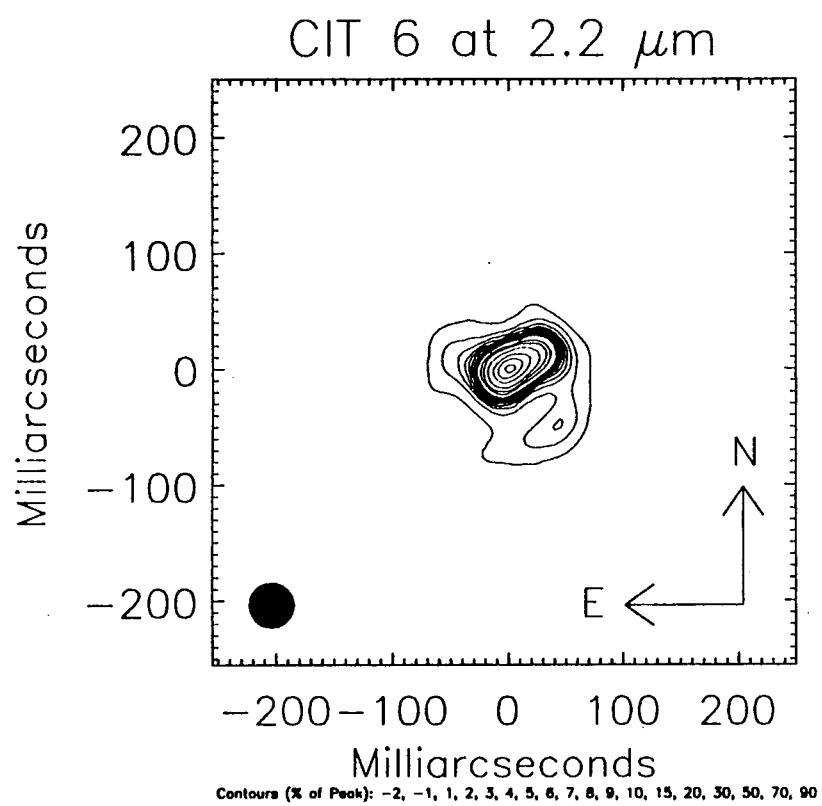
Power Spectrum
S Ophiuchus
Log Scale.

CIT 6 at 2.2 μ m (Jan 1997)



Visibility in U-V Plane





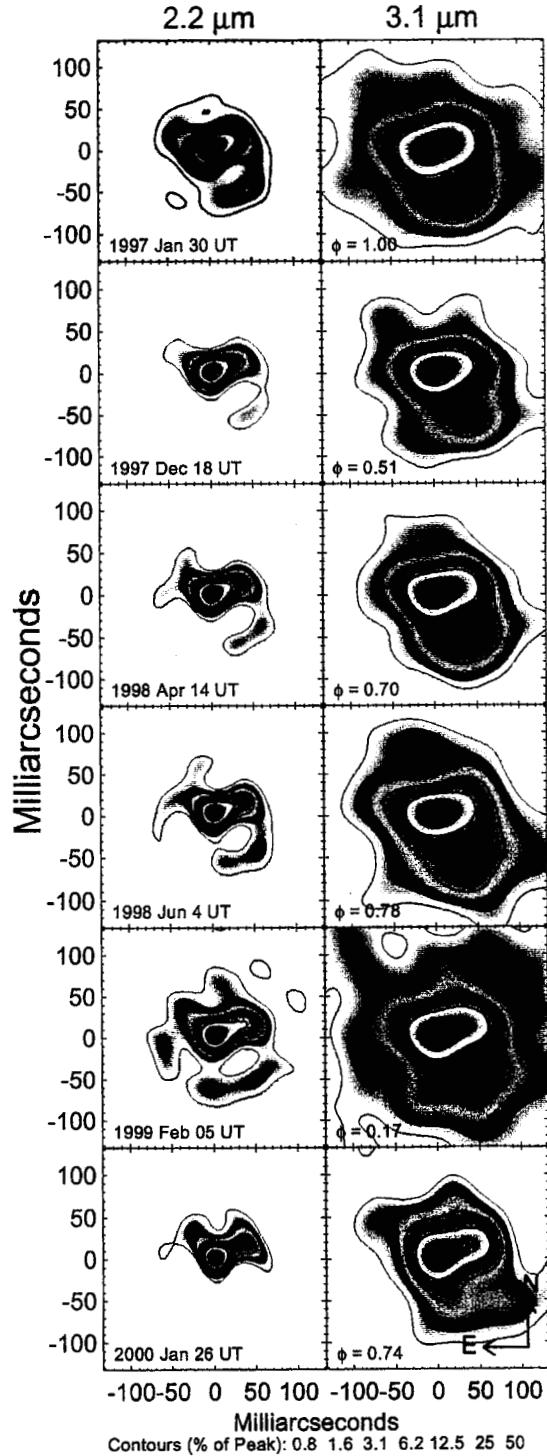
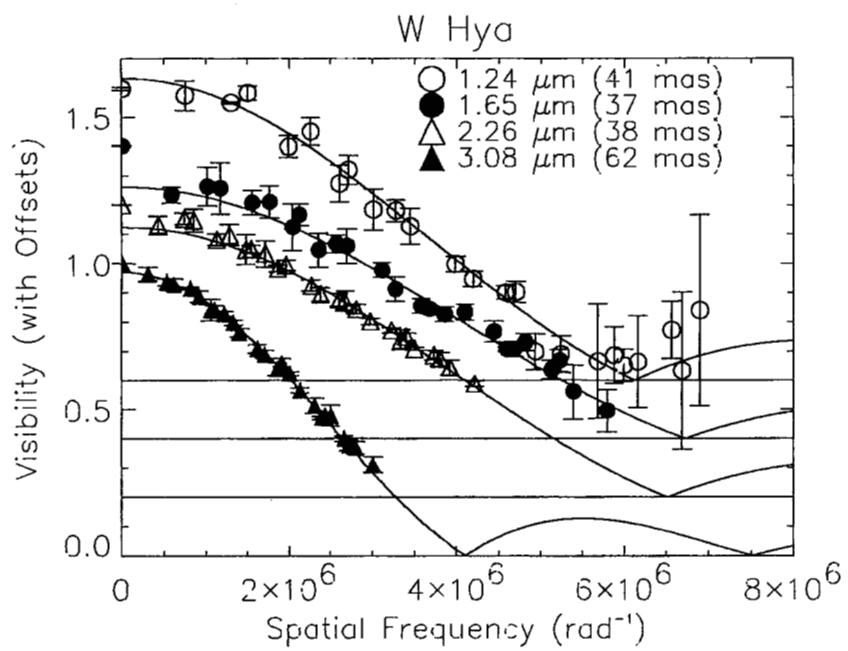
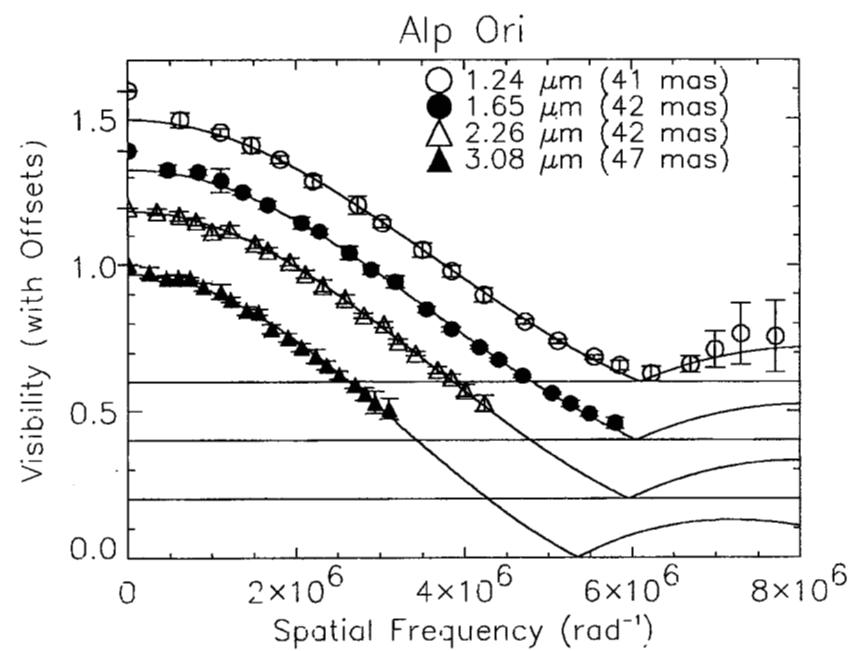
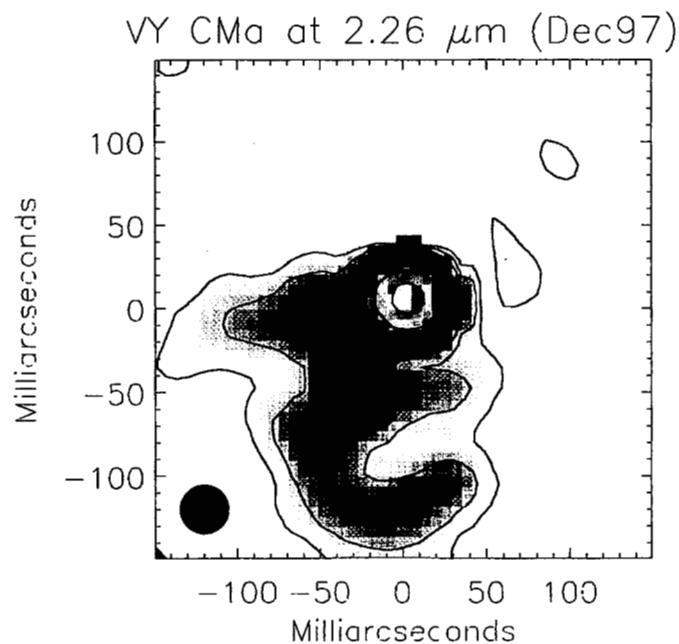
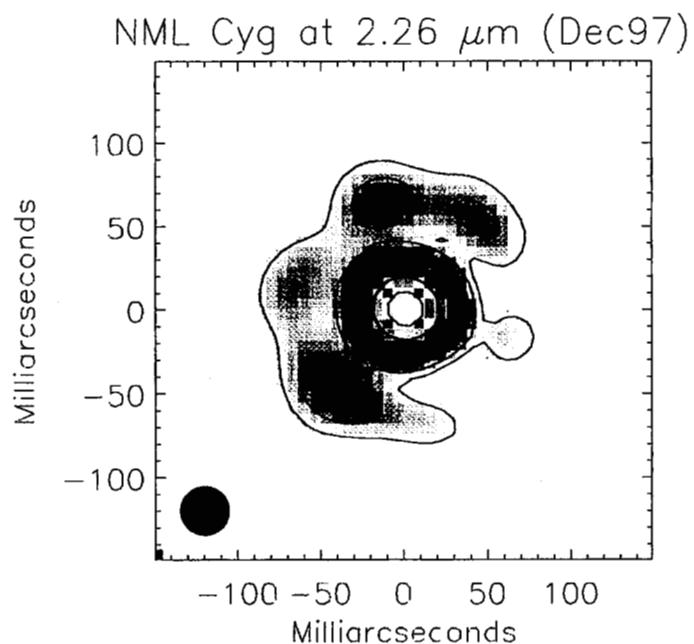
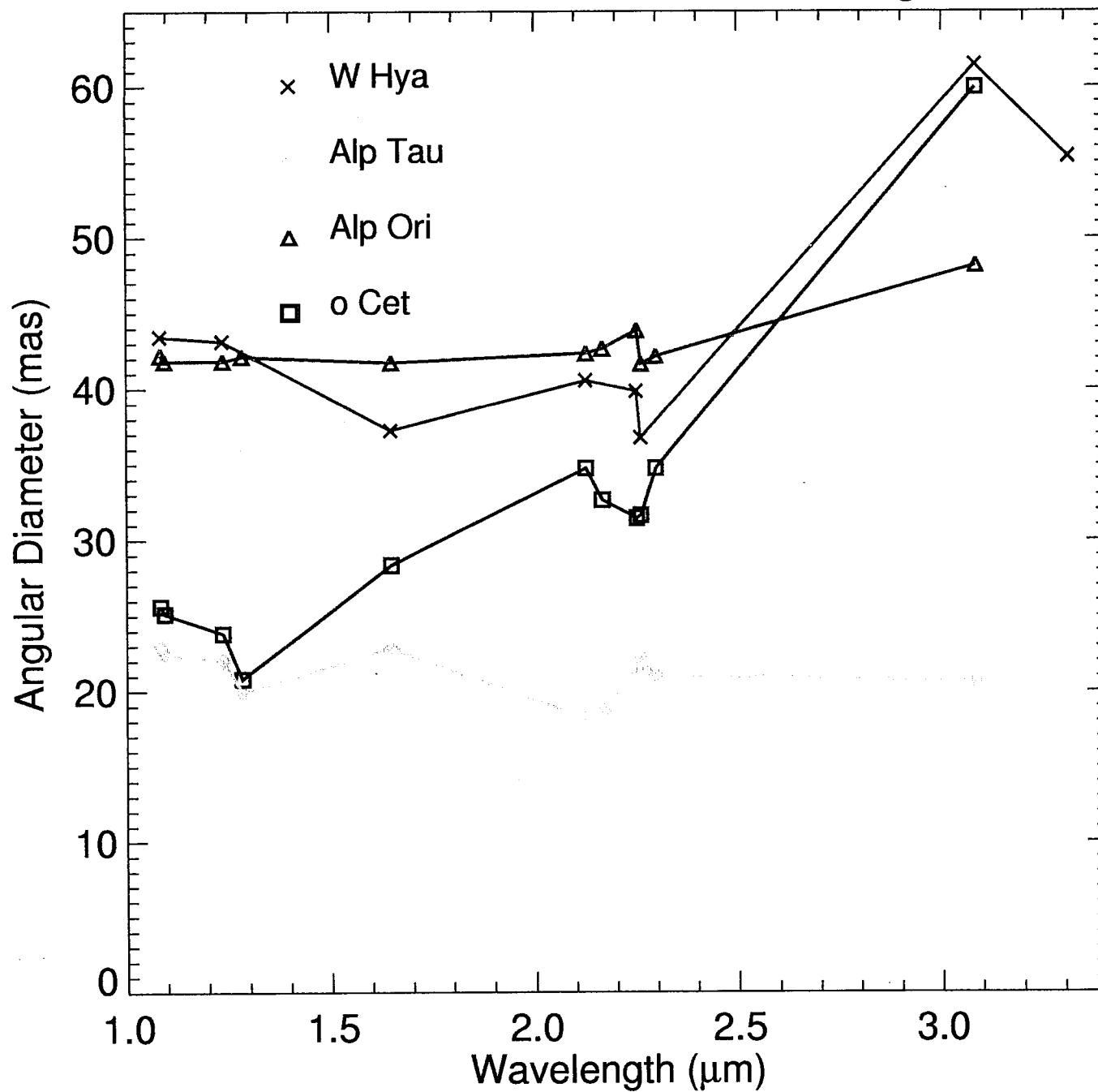


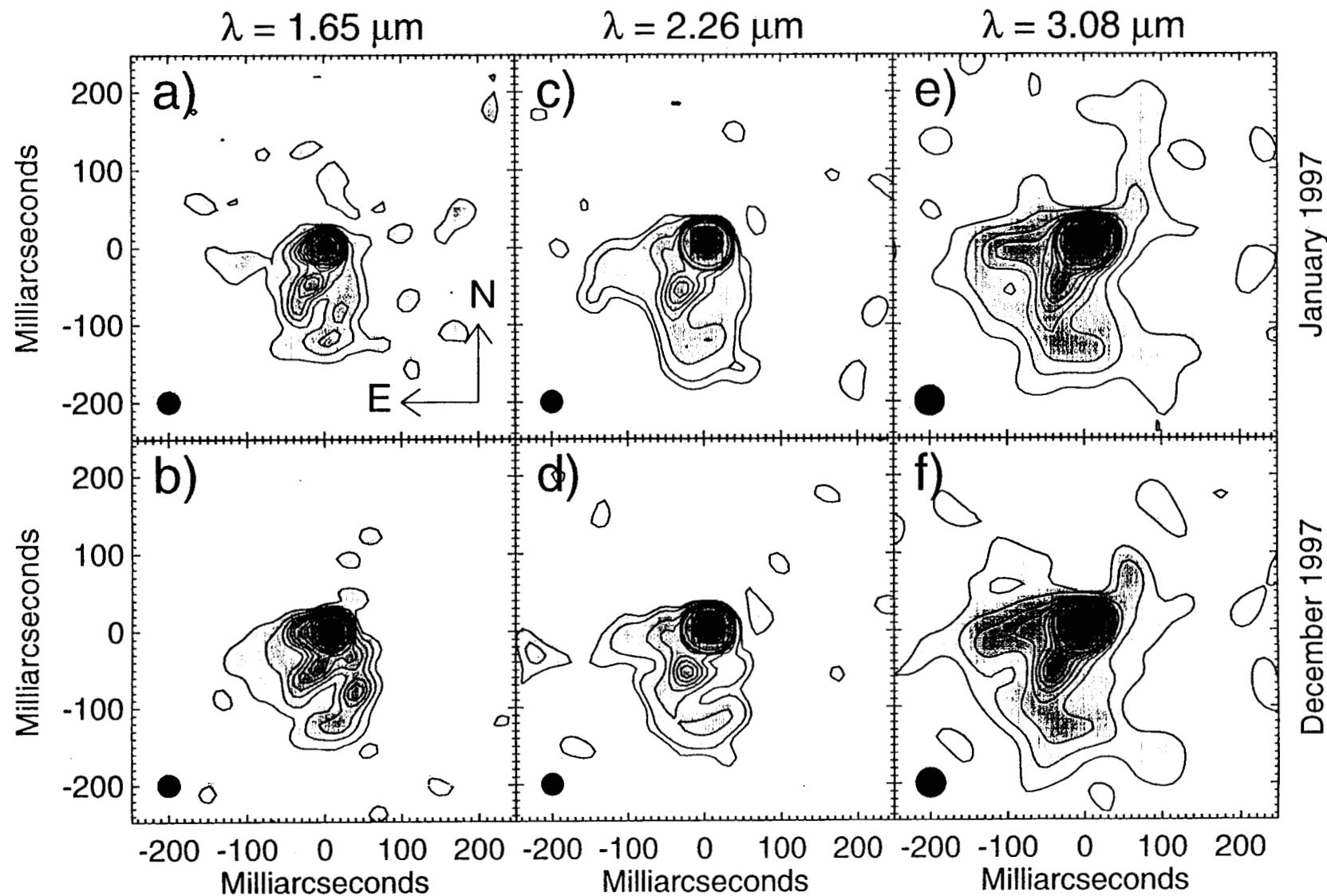
Fig. 1. Multi-epoch images of CIT 6 at $2.2\mu\text{m}$ (left panels) and $3.1\mu\text{m}$ (right panels). Each epoch is labeled by the U.T. date of observation and the pulsational phase of CIT 6 according to Taranova & Shchavrin (1999). Contour levels are logarithmic, each representing a factor of two, and are 0.78%, 1.56%, 3.13%, 6.25%, 12.5%, 25%, and 50% of the peak.



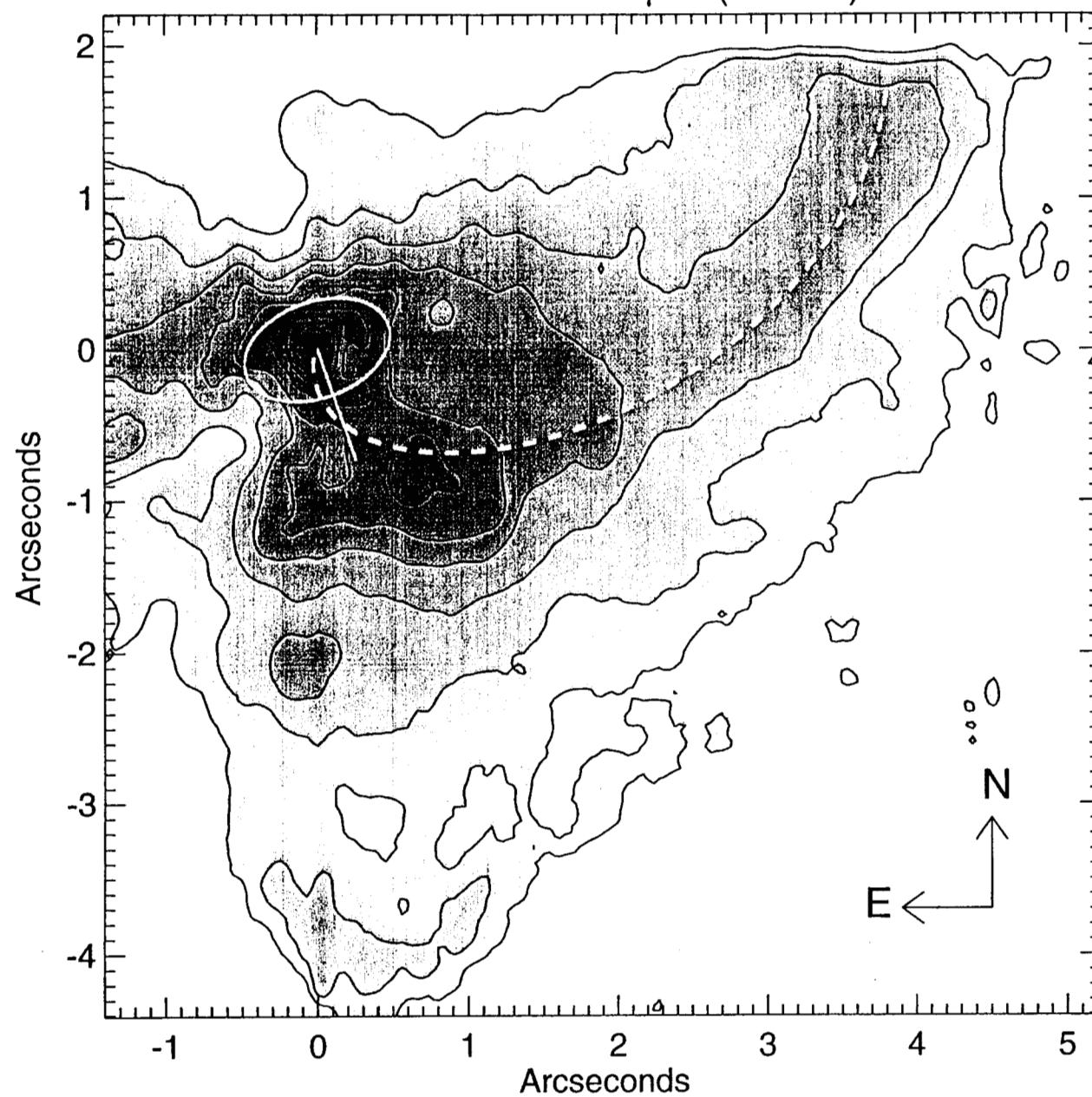
Stellar Diameter vs. Wavelength

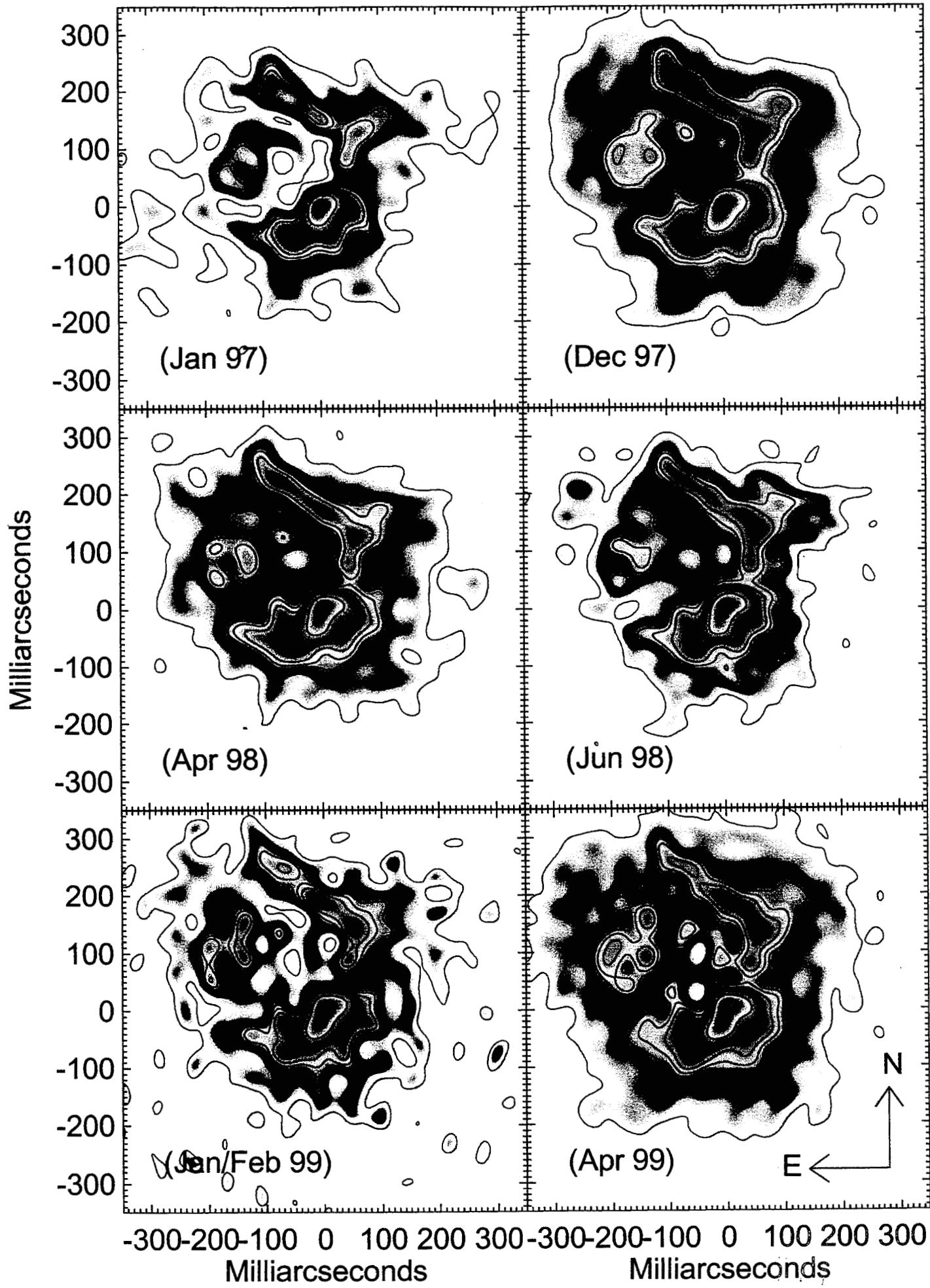


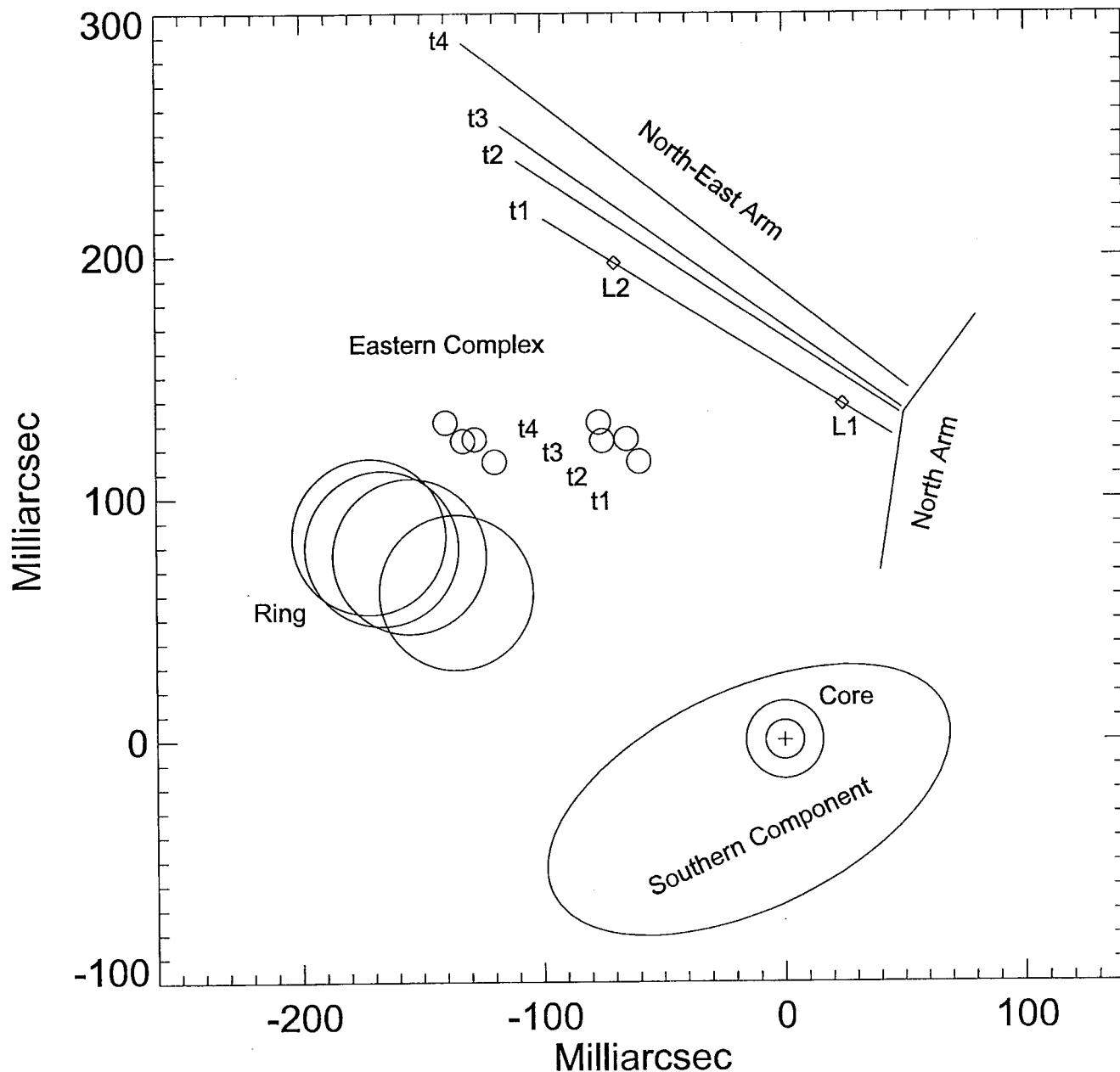
VY CMa

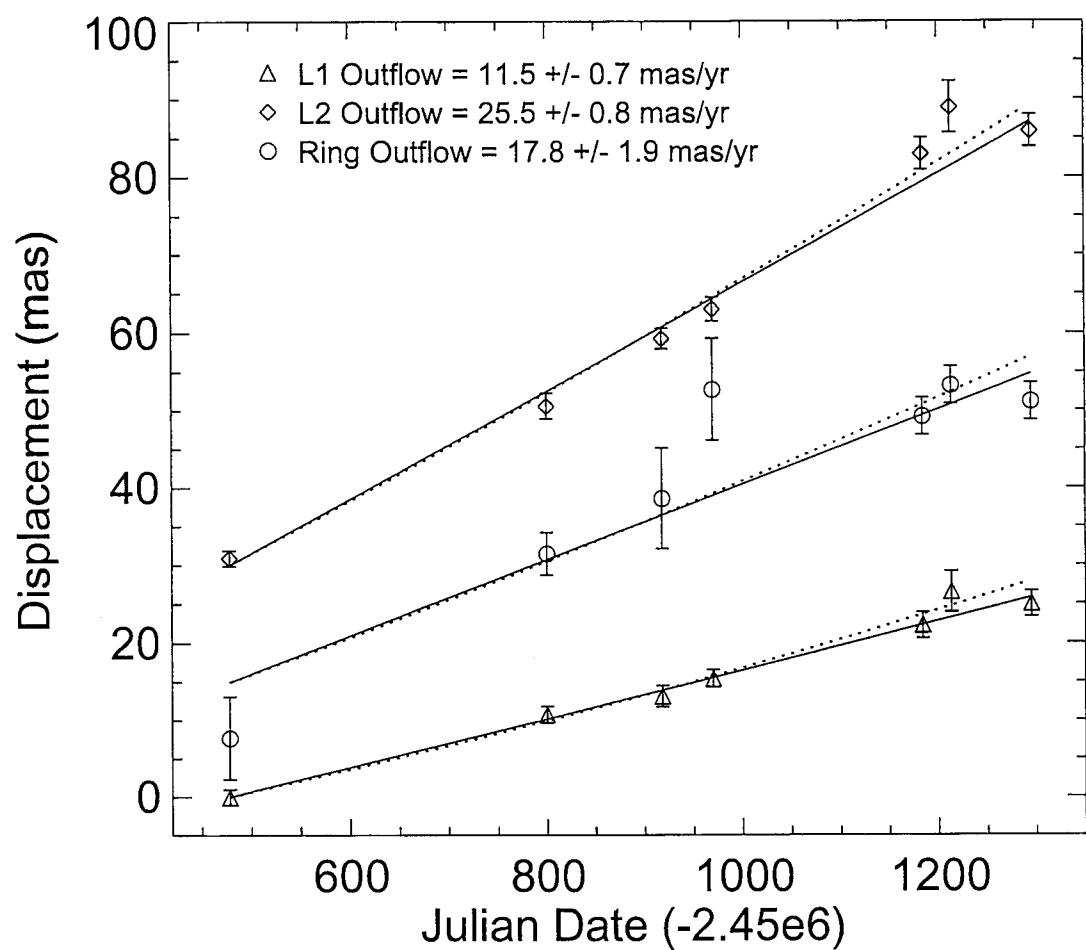


VY CMa at 1.25 μ m (Dec96)









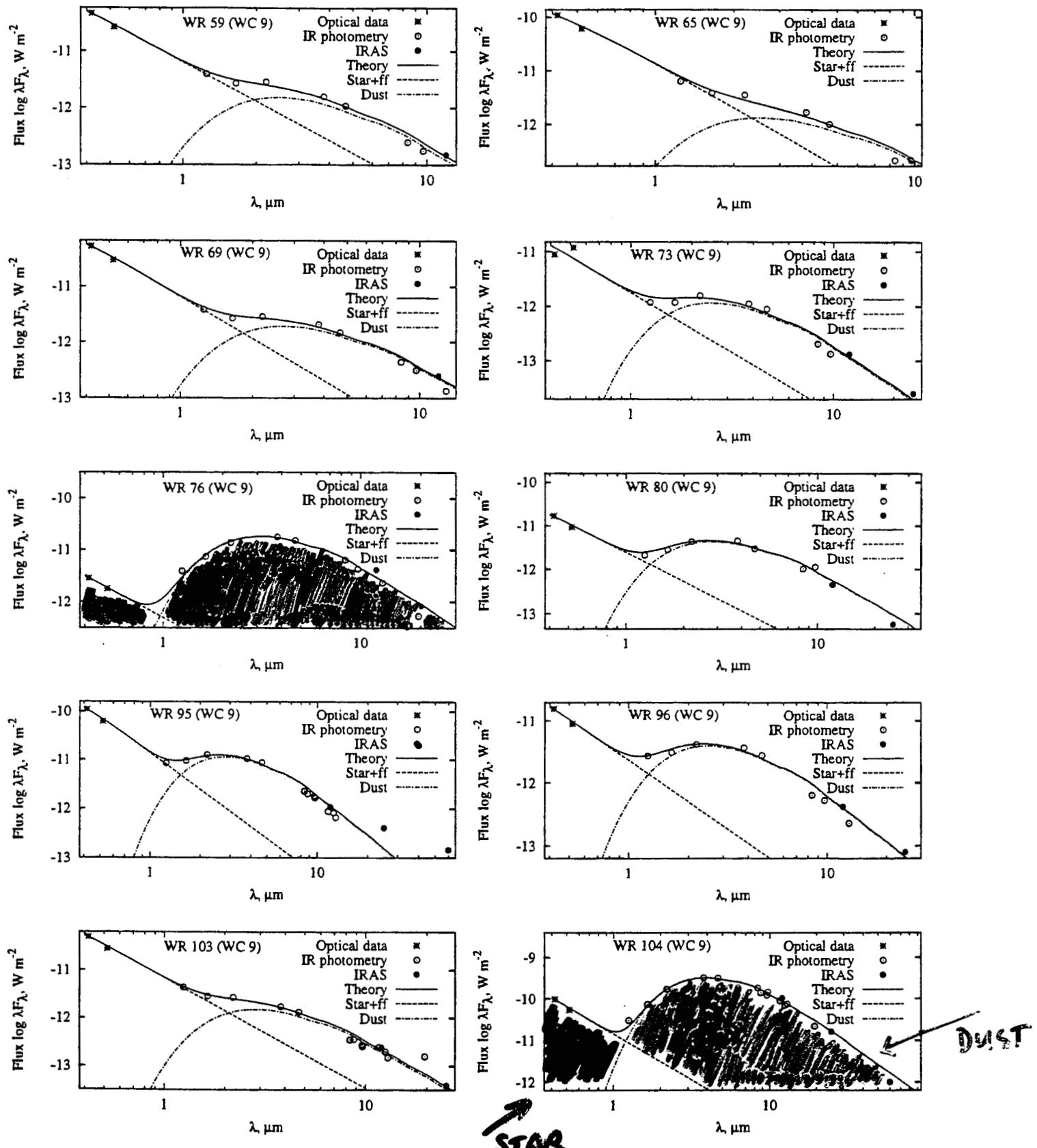
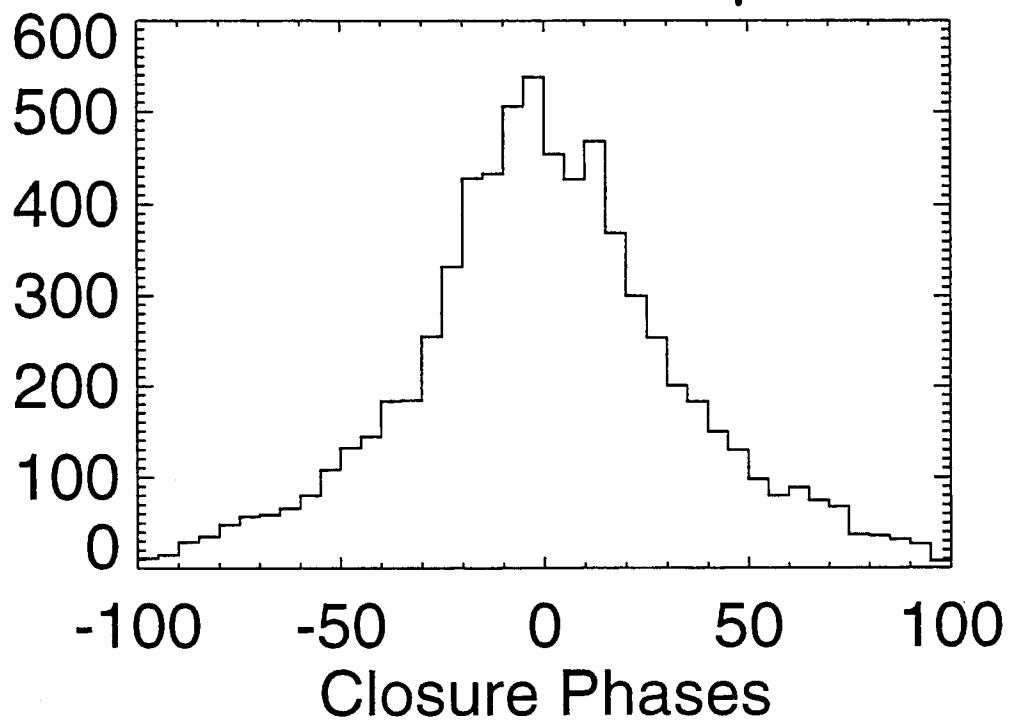
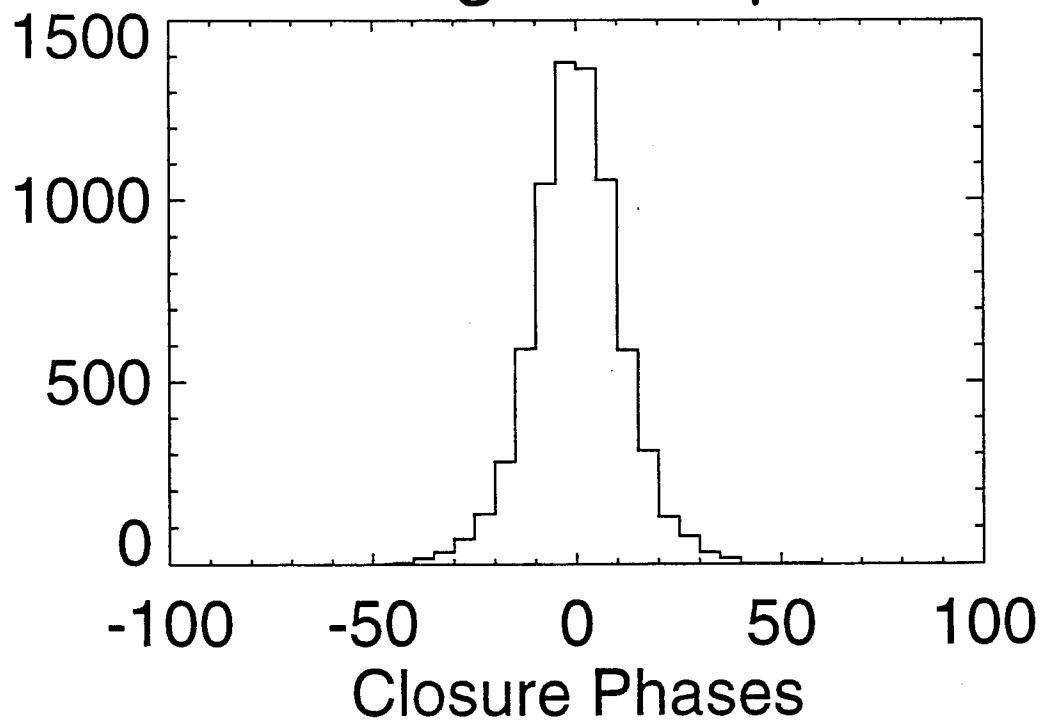


Figure 2. Observational and theoretical energy distributions of WR stars. The observational data are marked by asterisks (optical photometry), open circles (ground-based IR photometry) and filled circles (IRAS); the model spectra are depicted by solid lines and the contributions of 'star+wind' and dust emission by dashed and dot-dashed lines, respectively.

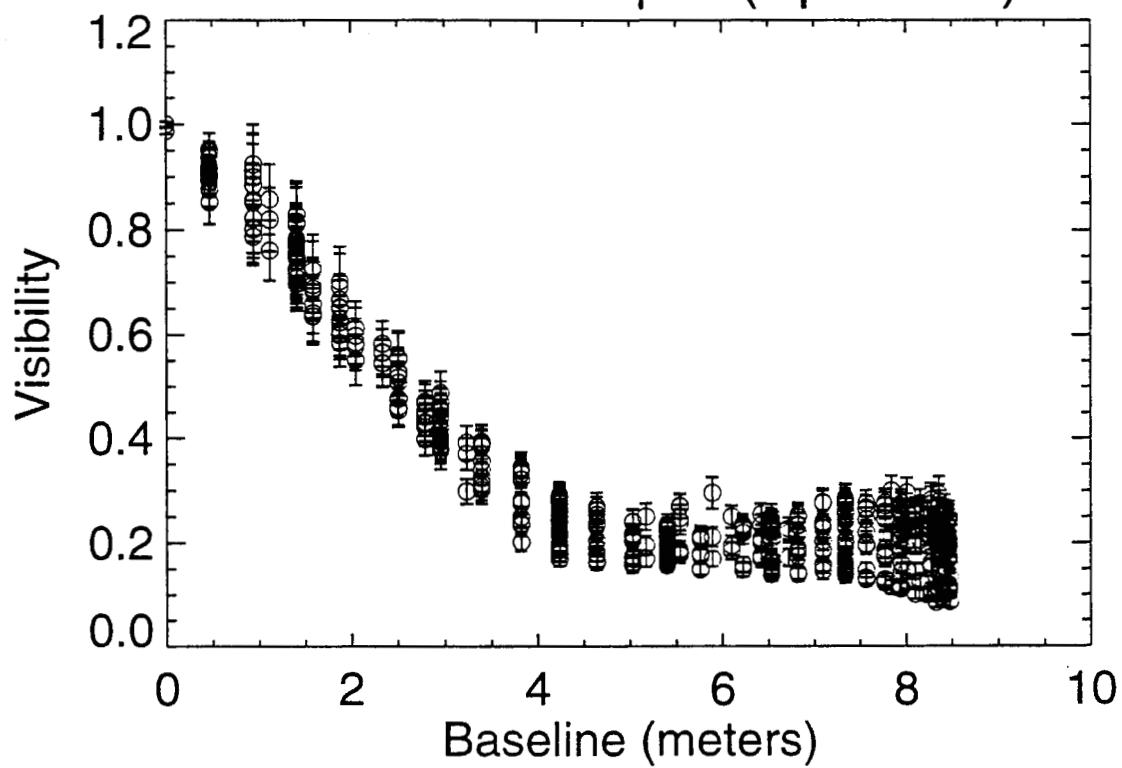
WR104 at 2.2 μ m



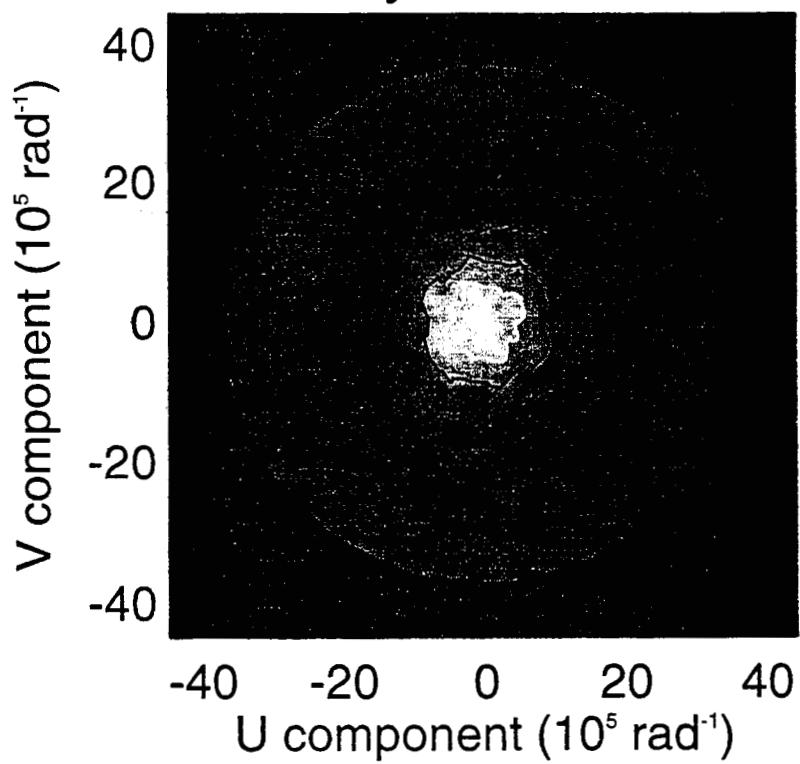
14 Sgr at 2.2 μ m



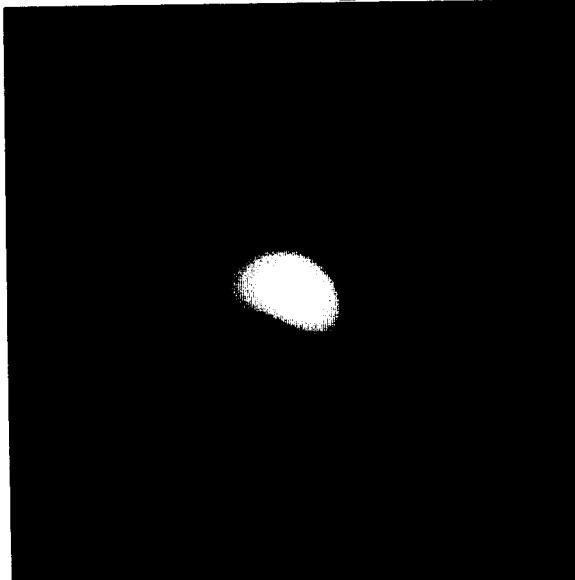
WR 104 at 2.2 μ m (Apr 1998)



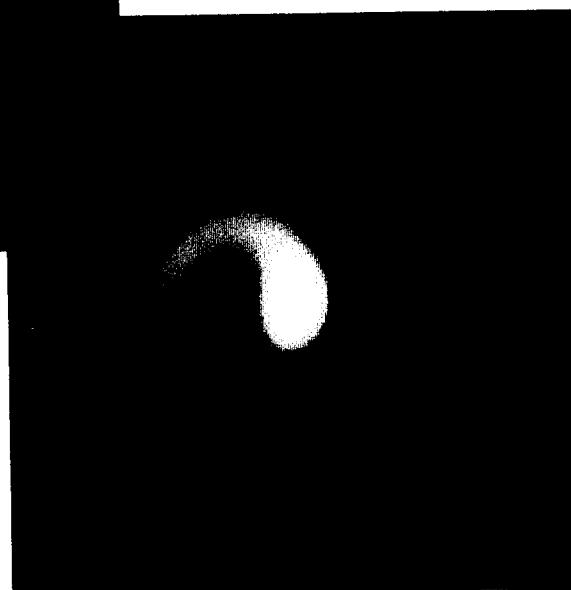
Visibility in U-V Plane



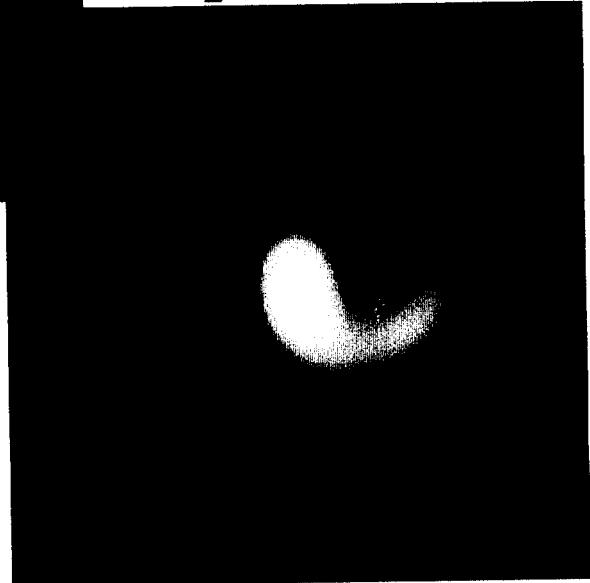
April 1998



June 1998

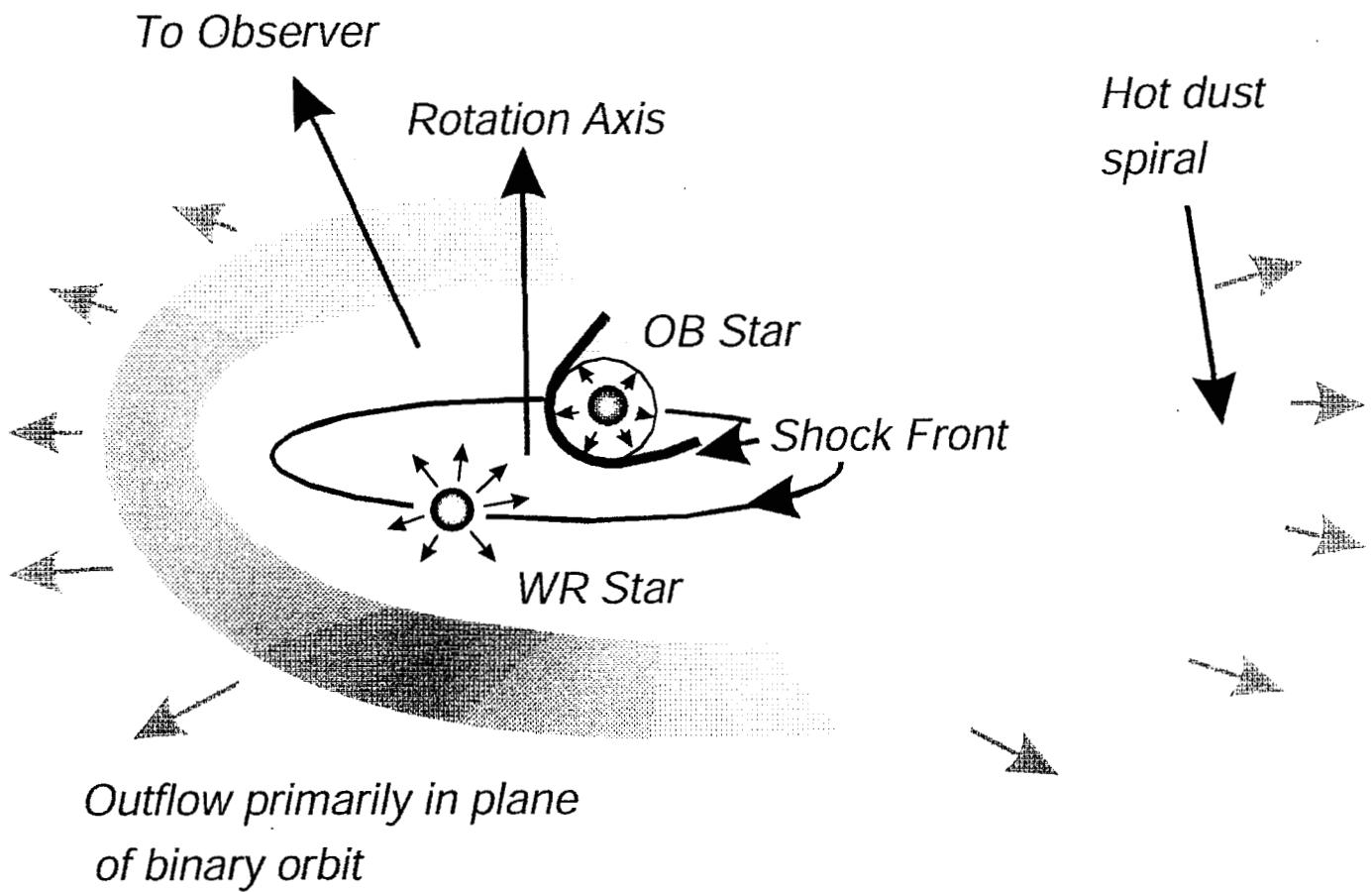


September 1998

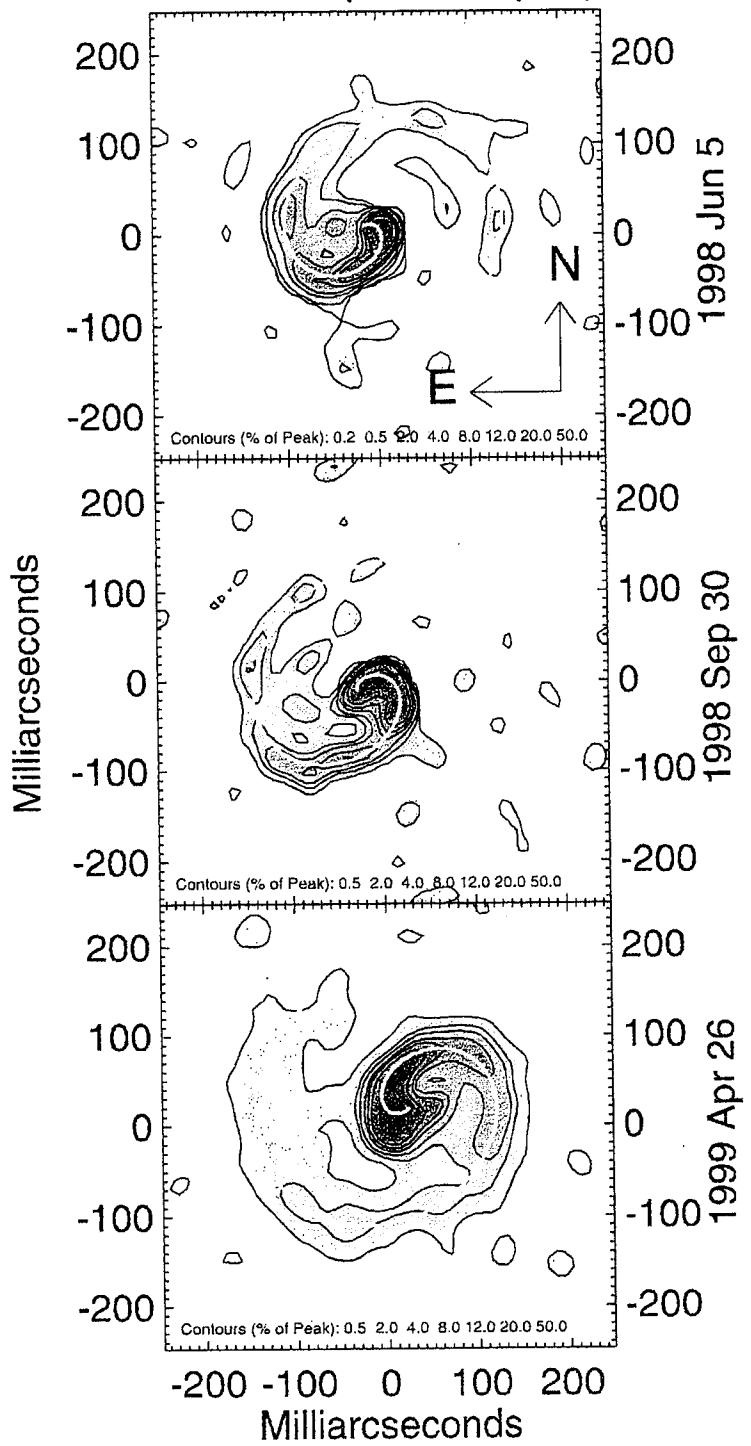


WR 104

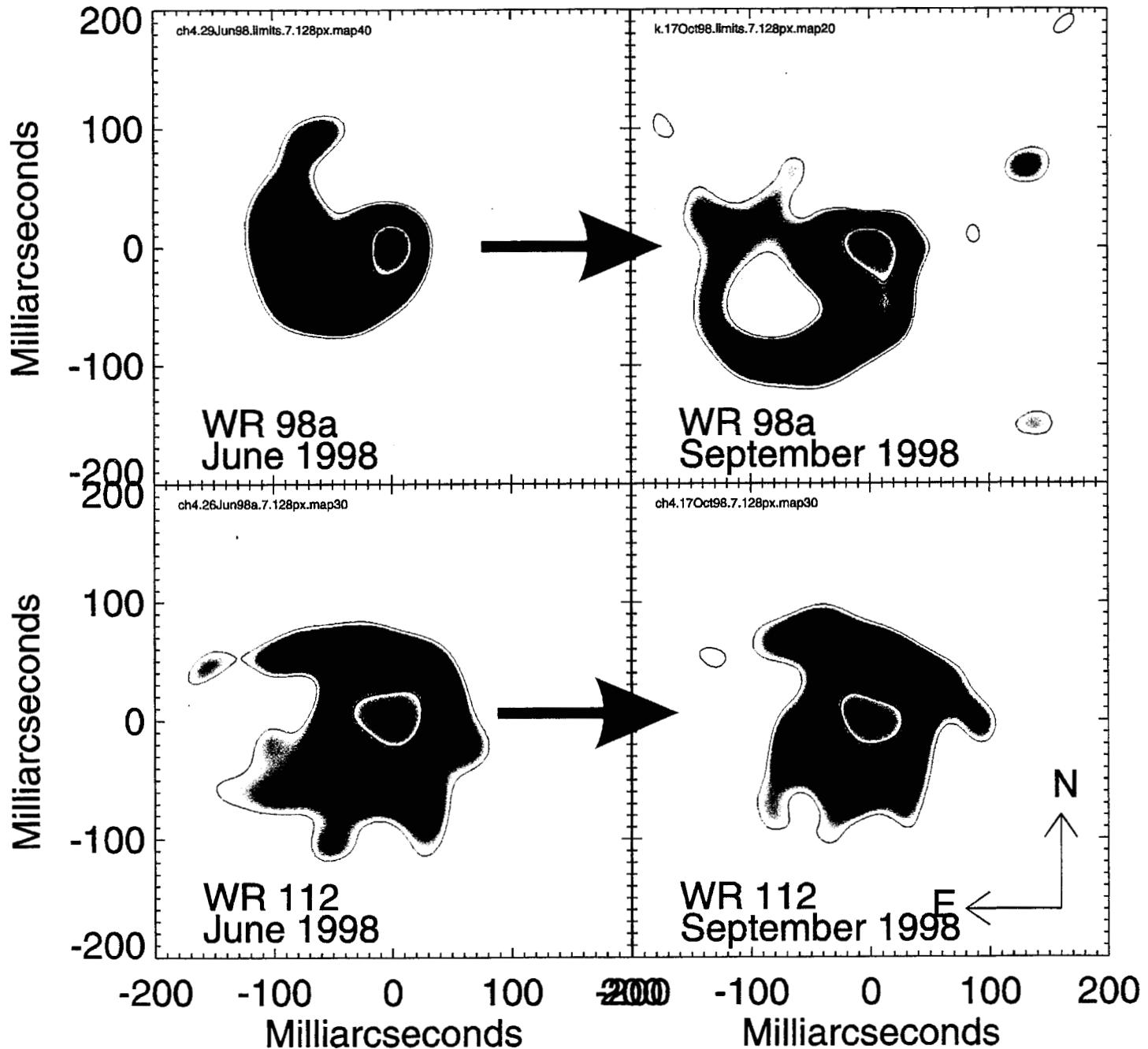
Interacting Binary Wind Model of Spiral Outflow Around WR 104



WR 98a ($\lambda = 2.2 \mu\text{m}$)



Wolf-Rayet Dust Shells (2.2 μ m)



Contours (% of Peak): 1 2 3 4 5 10 30 70

Herbig Ae/Be Disks -- theoretical picture

Weak stellar wind

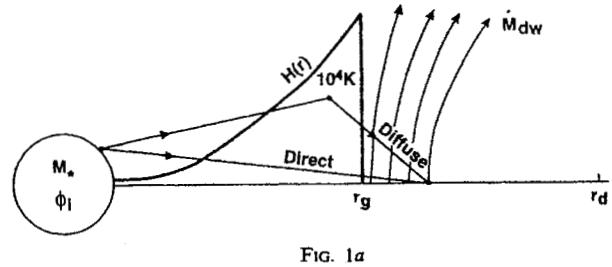
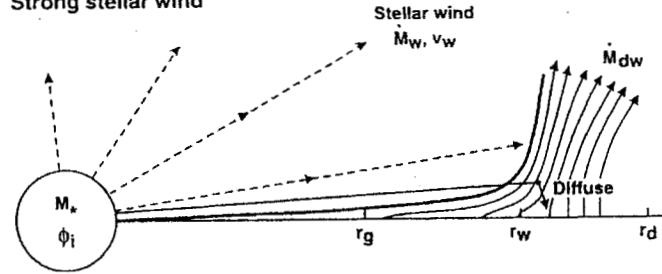
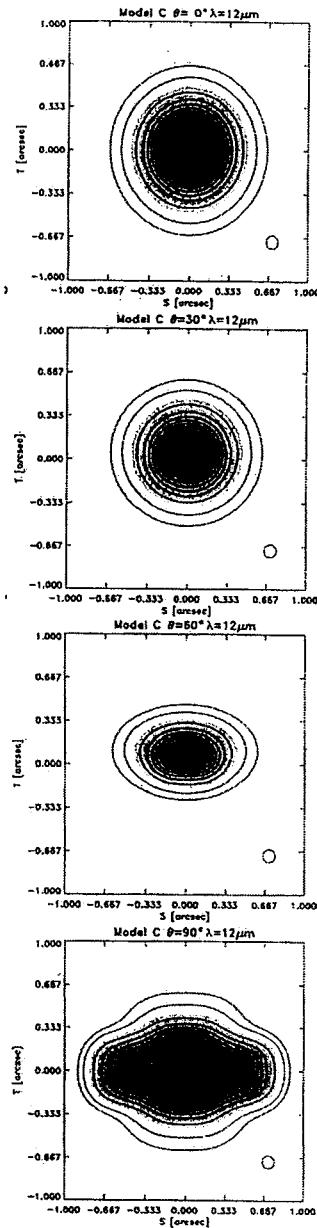


FIG. 1a

Strong stellar wind

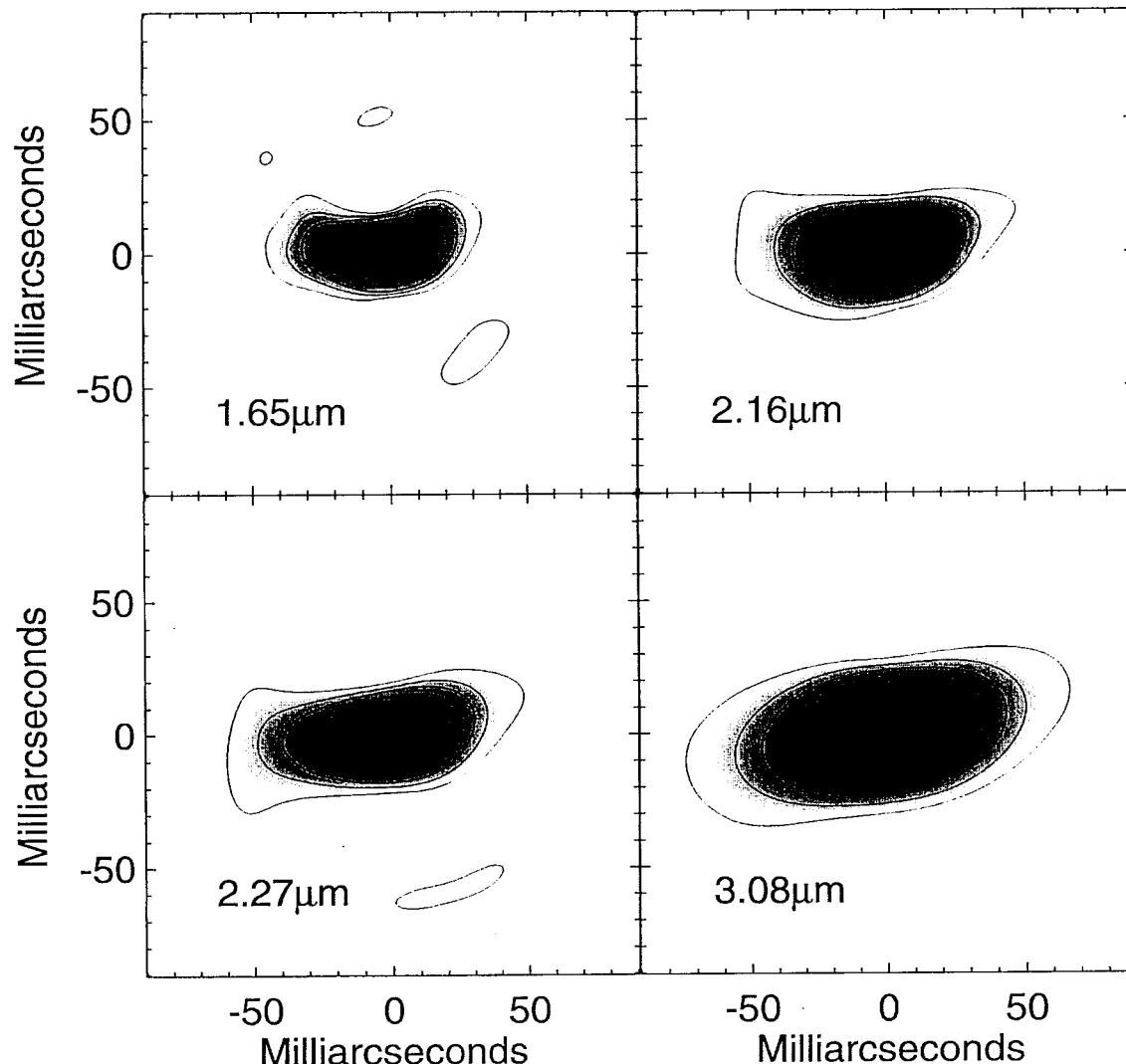


- Models of Massive Star Disks due to Hollenbach et al. and Yorke et al.
- Photoevaporating disks from intensive UV field from very hot star.
- Proposed to explain lifetimes of Ultracompact HII regions.
- Applicable to disks observed with Keck aperture masking experiment, i.e. MWC 349A and LkH α 101.
- Detailed radiative transfer models really needed, but early papers give useful semi-quantitative information.



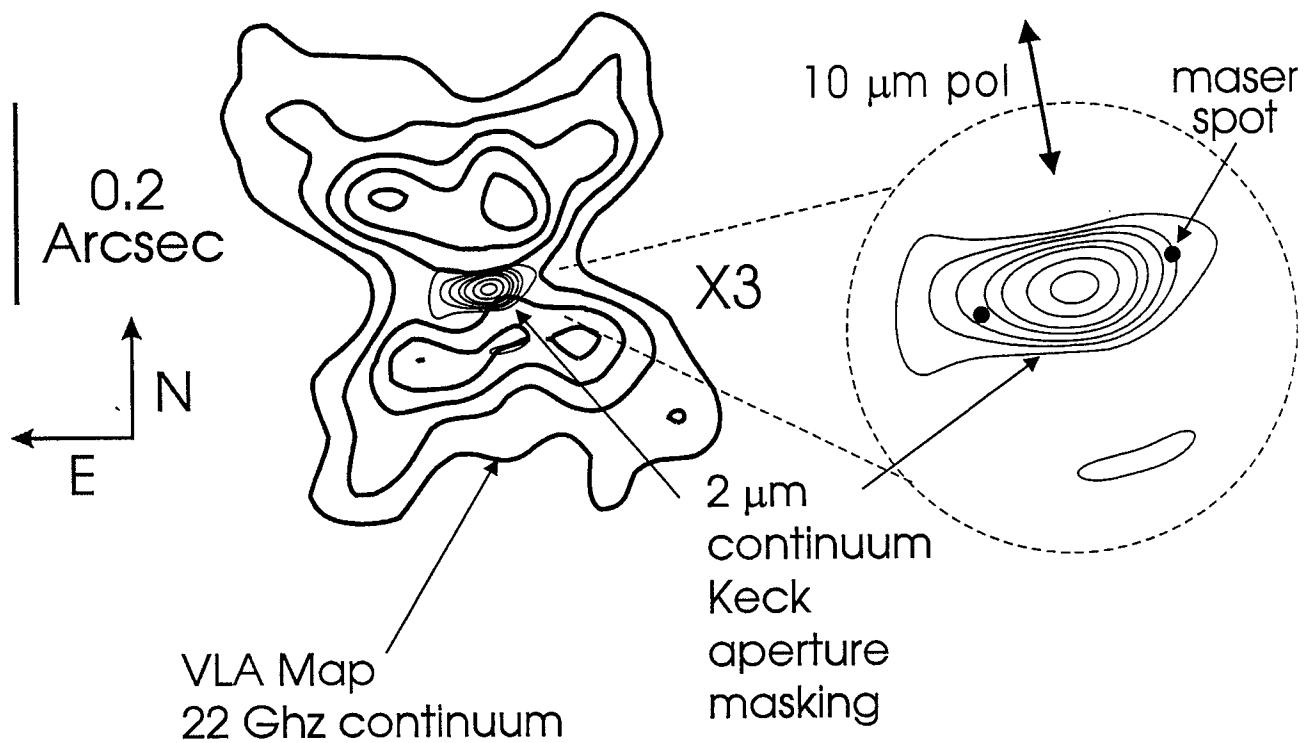
- Models of Kessel, Yorke, et al. (1998) predict appearance of images of stars such as MWC 349A.
- On the left are 2-D radiative transfer results for 12 μm .
- Need models for 1-3 μm for Aperture Masking results.

MWC 349A -- A Herbig Oe/Ae/Be Star with a Disk



Contours (% of Peak): 0.4 1 2 5 10 30 70

MWC 349A



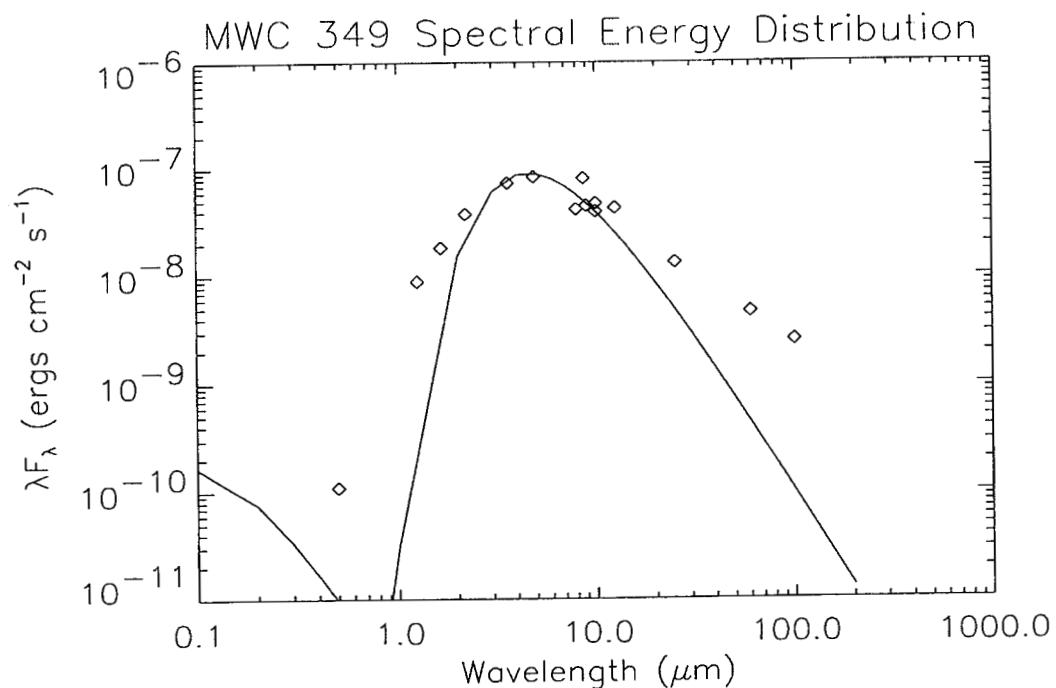
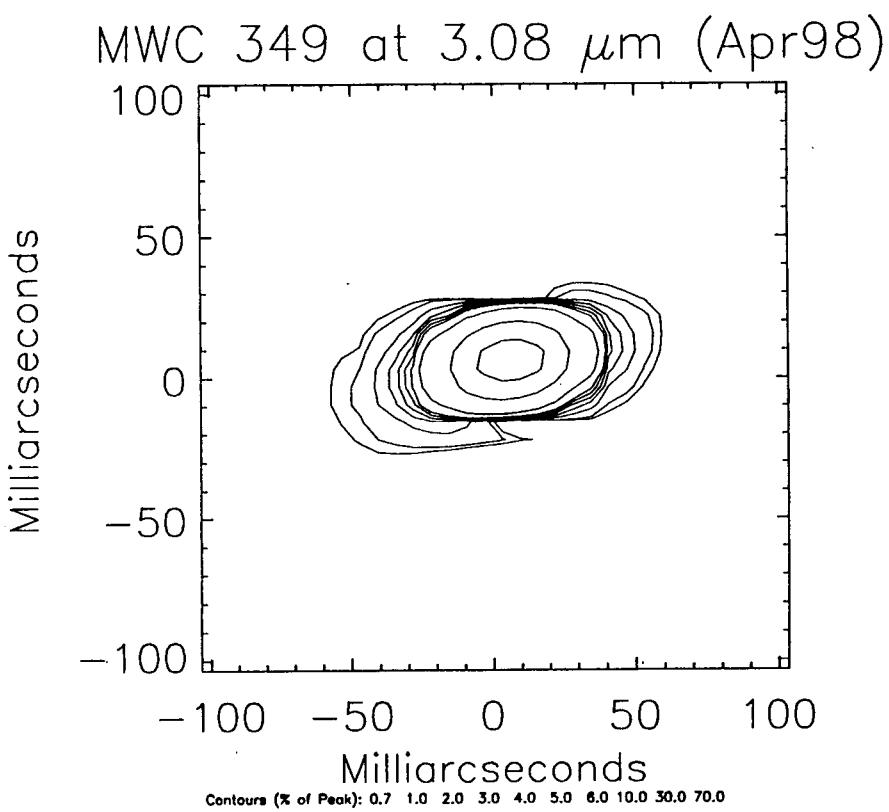
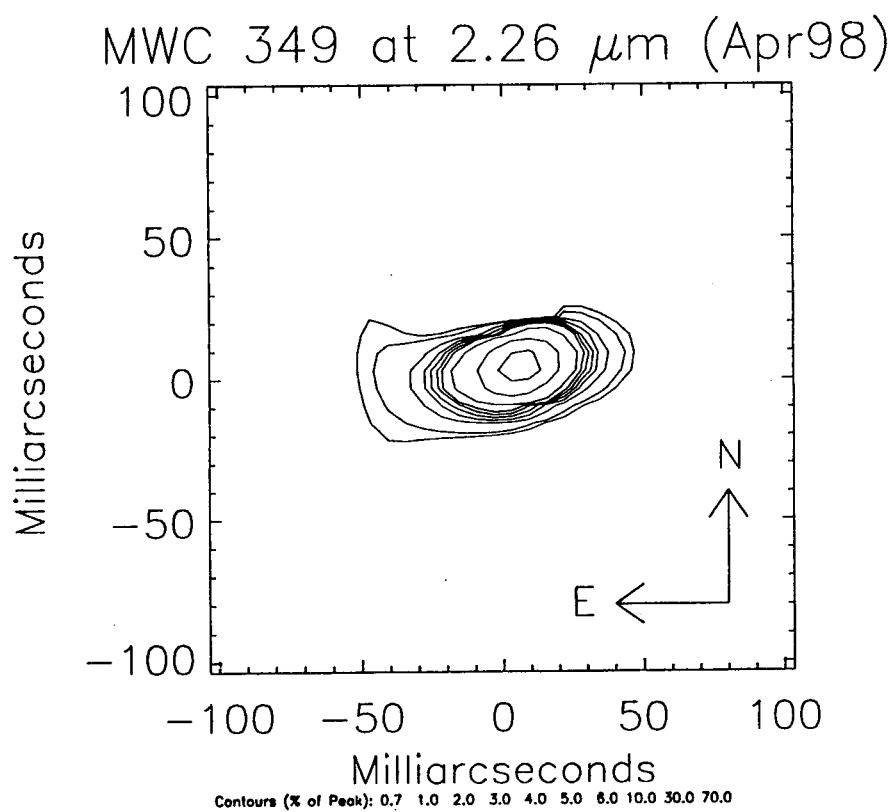
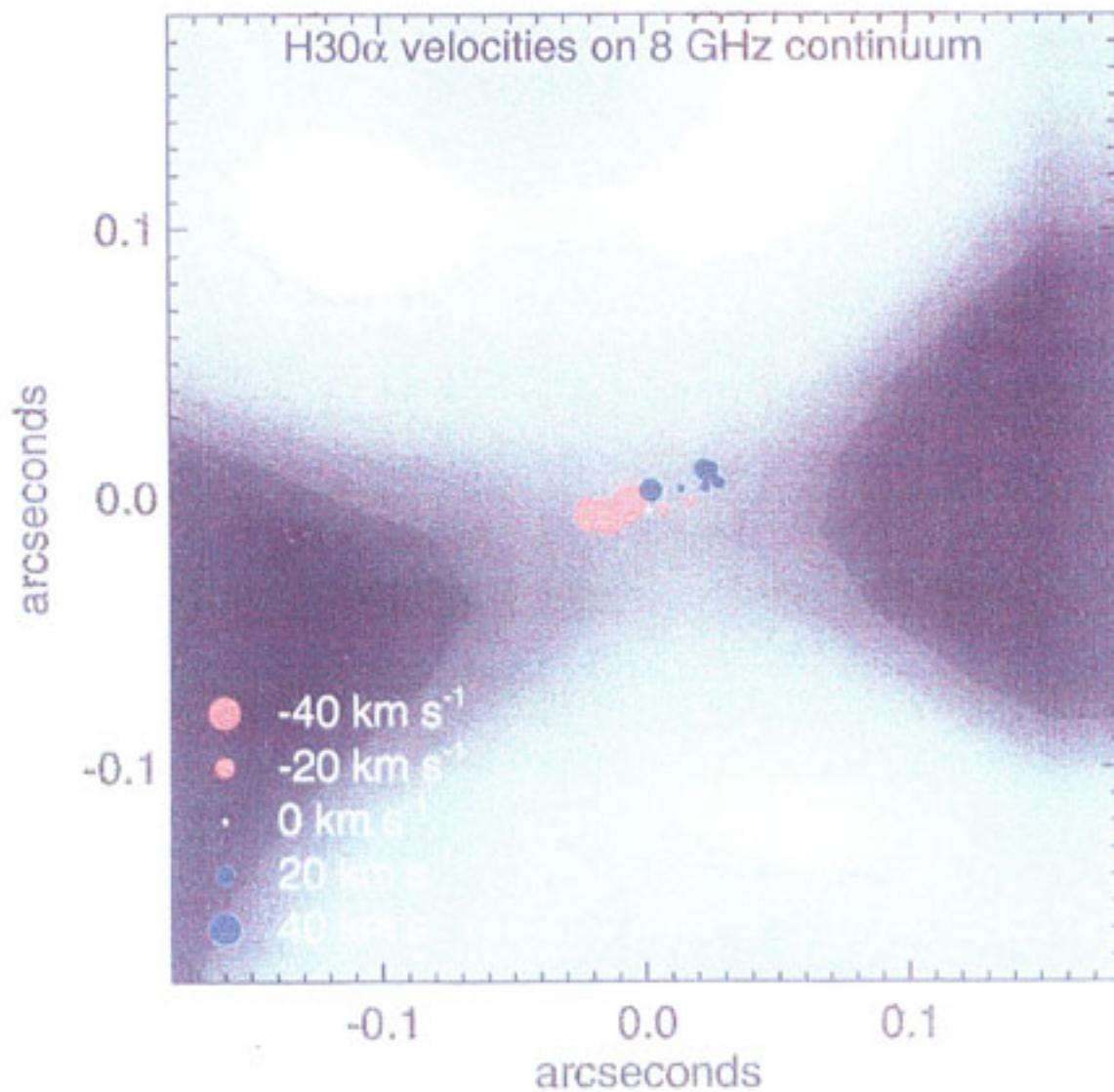


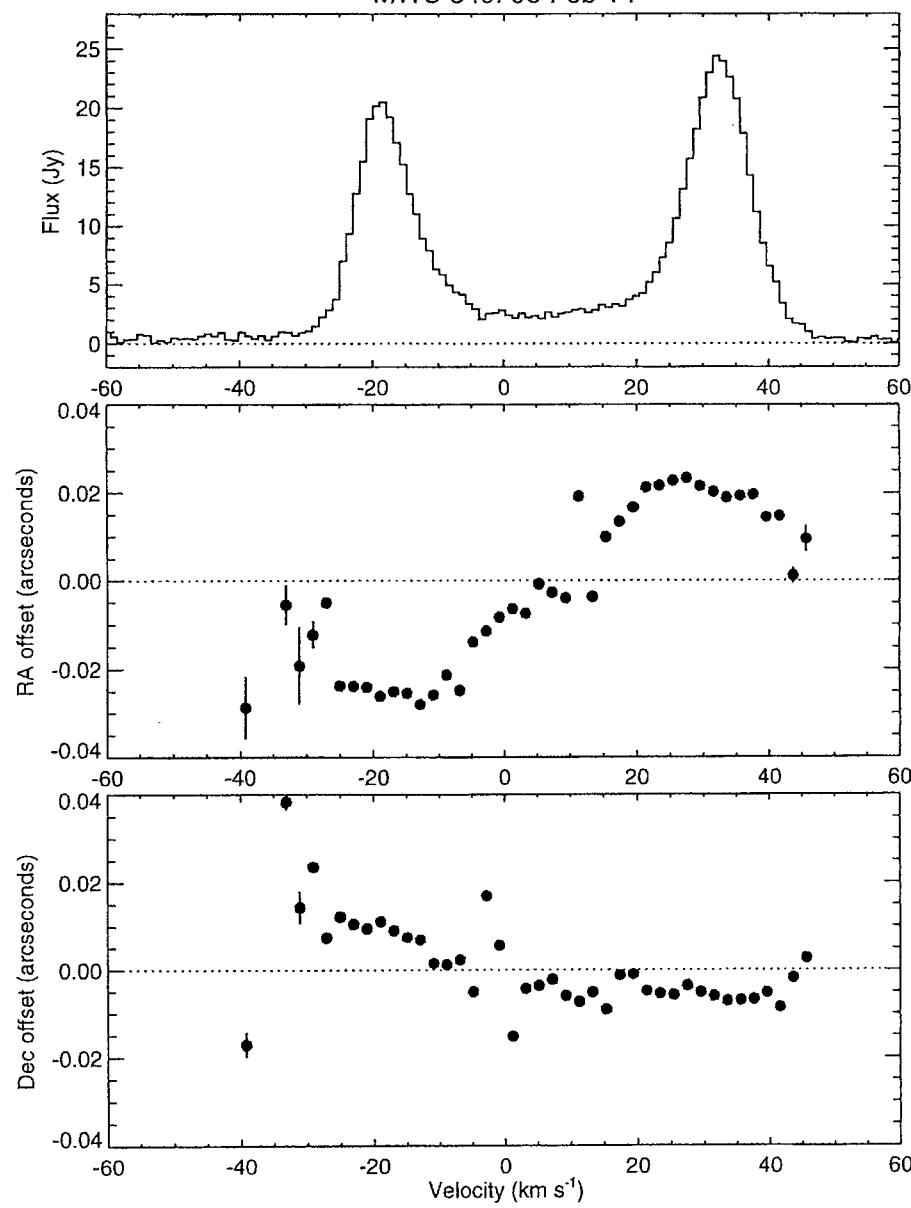
Table 2. Summary of Elliptical Model Fits

Filter Wavelength (μm)	FWHM (mas)	Axial Ratio	Position Angle (Degrees)
1.65	36.1 ± 1.9	0.52 ± 0.1	100 ± 3
2.25	46.7 ± 2.2	0.44 ± 0.08	99.1 ± 2.4
3.08	61.7 ± 1.4	0.57 ± 0.03	100.2 ± 2.2

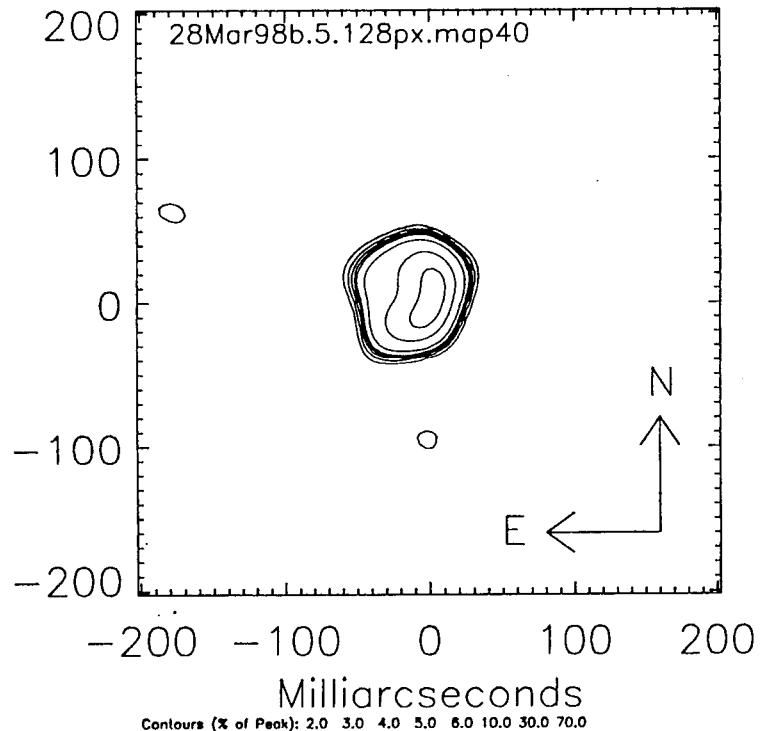




MWC 349: 98 Feb 14



LkHa 101 at 2.26 μ m (Apr98)



LkHa 101 at 2.26 μ m (Apr98)

